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# PREFACE

This is the first number of Vol. 52 of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers. It embraces the Institute's annual Pacific Coast convention held at Vancouver, B. C., August 30 to September 2, 1932, and the Middle Eastern District (No. 2) meeting held at Baltimore, Md., October 10-14, 1932; includes all of the technical papers and related discussion presented at these meetings that were recommended for publication.

Also there are included the recommended technical papers and related discussions presented at the first three sessions (automatic stations, electric welding, and communication) of the Institute's annual winter convention held in New York, N. Y., January 23-27, 1933. The remainder of the recommended 1933 winter convention material is scheduled for inclusion in the June 1933 quarterly number of the TRANSACTIONS.

A complete table of contents may be found on the first page, and the customary alphabetical index of authors on the last page.

As an explanation of inevitable inconsistencies that may be noted in this and the next subsequent numbers, it is significant to note that a change has been made in the basic reference dictionary by which the editorial staff is guided in the preparation of copy for publication.

Beginning January 1, 1933 "Webster's International Dictionary" (G. & C. Merriam) was adopted as the editors' guide and arbiter for all published matter. Material composed for publication since January 1 follows the new guide but, for economical reasons, standing material will not be changed. Thus, the two styles may appear side by side until all standing material has been published.

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This issue, Number 2 of Vol. 52, of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers, contains the remainder of the papers and related discussion presented at the Winter Convention, New York, N. Y., January 23-27, 1933. The papers presented at the first three sessions of this meeting were published in the March 1933 quarterly number of the TRANSACTIONS.

The material presented at the North Eastern District meeting, Schenectady, N. Y., May 10-12, 1933, and the Summer Convention, Chicago, Illinois, June 26-30, 1933, and recommended for publication is scheduled for inclusion in the September quarterly.

A complete table of contents may be found on the first page, and an index of the authors included in this issue is appended. The complete annual index will appear in the last quarterly of this volume.

As an explanation of inevitable inconsistencies that may be noted in this and the next subsequent numbers, it is significant to note that a change has been made in the basic reference dictionary by which the editorial staff is guided in the preparation of copy for publication.

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# Segregation of Hydroelectric Power Costs

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## Introduction

The economic and physical conditions of the territory served by an electric utility as well as the conditions of the utility itself are continually changing, which makes it important to analyze the different cost items periodically in order to determine the trend of the changes in costs that are taking place. An increase in system load requires new generating plants, transmission lines, distribution lines and substations, the cost of which varies and in turn varies the cost of power. The cost of distributing power varies with changes in the character and location of the load. The overall cost of power will also change with a change in wages, cost of fuel or cost of supplies and materials. An analysis of system power costs is of importance to the various electric utility engineers, as well as to the management, if the information is in such form as to be readily usable for their particular problems.

The analysis of the power costs of a hydroelectric generating station is complicated by the fact that no two hydro stations are alike and by the fact that the method of using the station in conjunction with the rest of the system determines how costs may be segregated. The following discussion is divided into three parts. The first section is a brief outline of the method used in segregating system power costs and the development of the fundamental cost items. The principles upon which the cost of power is usually based are stated in order to show how any section or group of unit costs fit in and effect the entire system costs. The second section has to do with the segregation of the power costs of hydroelectric stations into their component parts. The methods of developing the components for different classes of hydro stations are outlined. The peculiarities of hydro power are given in the last section and the method of determining an average cost of power for a hydro unit or hydro system is outlined.

## I—Outline of System Power Cost Analysis

The analysis of system power costs consists: first, of dividing the system into its component parts and determining the yearly expenses of each part; and second, of prorating the different yearly expenses for each division between demand costs, energy costs, customer costs, and any other special costs that may be of interest. The main divisions which are applicable to the usual system are as follows: Production, transmission, distribution, customer costs, and general costs.

In addition to the above, any special costs that do not apply to the system in general should be kept separate. Street lighting costs where the utility maintains the lighting system, street railway costs where operation and maintenance is by the utility, and electric appliance sales costs are examples of costs that should be kept separate.

The annual production costs can be prorated between different generating plants. The transmission, distribution, and customer costs divisions can each be divided into geographic divisions. The general costs are prorated between production, transmission, and distribution. With the above divisions of costs, the cost of power at any particular point on the system can be obtained.

The segregation of annual costs between demand, energy, and customer costs is the basis for the so-called three-part rate structure which has been in existence for many years. While the usual rate structure does not include the customer costs as a special item, it is recognized as one of the costs of power and is included with the demand costs. The demand costs are those costs that are proportional to the power or kilowatts, but are independent of the amount of energy used. The energy costs are those costs that vary with the energy used and are proportional to kilowatt hours. Customer costs are costs chargeable to each customer that are independent of the amount of power or energy and which are approximately the same for each customer.

The segregation of production, transmission, and distribution into demand costs and energy costs requires a careful analysis of how the equipment is to be used and how the costs are incurred. On steam generating plants, the annual fixed costs are assumed to be demand costs and the variable costs are energy costs. Distribution and transmission annual costs are usually considered demand costs.

In ascertaining the cost of power on most systems, the utility can be considered a "going concern" with a built up load that is usually growing. It is advisable to keep at all times a certain percentage of reserve capacity both in kilowatts for peak demand and kilowatt hours. The amount of reserve capacity is a matter of judgment determined from experience and is different on every system.

## II—Analysis of Hydroelectric Power Costs

The hydroelectric power station annual costs are practically all fixed costs; that is, the costs are about the same whether the plant turns out 5 per cent of the available energy or the maximum amount. The operating and maintenance expenses are the same regardless of the load factor on the plant, for supervision of a plant is required whether the turbines are operating or not. A small change could be assumed due to the increased maintenance with greater use and the change in the number of men required for continuous operation as against part time operation. The large items of the annual expenses are interest, depreciation, taxes and insurance due to the large investment required, which are fixed regardless of whether the plant operates or not. On first thought this would lead to the conclusion that all hydro costs are in the nature of demand costs, which is only true for certain hydro stations.

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The energy output of a hydro station is limited to some potential value determined by the stream flow of the river. It may not be possible to use the entire potential output due to the fact that the periods of high stream flow do not necessarily occur at such a time as they can be used on the system, or the installed generating capacity may limit the output to the machine rating. Most hydro stations have some pondage or storage which makes them more valuable to the system in that more potential energy in the stream becomes available to meet the system load.

The cost of constructing a given hydro project will vary with the amount of generating capacity that is to be installed. However, the amount of variation is usually small in comparison to the total cost of the project. As an example, assume a hydro project having a fixed stream flow for a period of 24 hours with pondage available to store the entire flow for 12 hours. Under these conditions the same total energy can be turned out in 12 hours as is possible in 24 hours if the generating capacity of the plant is at least double the capacity required for continuous 24-hour service. In order to increase the maximum kilowatts above that required for a 24-hour continuous duty the plant requires additional capacity in the turbines, generators, transformers, oil circuit breakers, electrical buses, penstocks, water conduits, power house and surge tanks. The cost of the dam, reservoir, water rights, and lands are approximately fixed and in most cases represent the bulk of the cost of the project. It follows then that as the plant factor goes down, the cost per kilowatt of the project also goes down and the total annual costs are increased only the amount necessary for the added depreciation, taxes, insurance and interest.

The original cost of a project can be divided into three classifications; first, those costs which are approximately proportional to the generating capacity; second, those costs which are independent of the generating capacity; and third, those costs which would apply to both groups. Individual plant items are segregated in the following list in accordance with the above classification.

| Proportional to generating capacity | Independent of generating capacity | Proportional and independent |
|---|---|---|
| Turbines | Dam | Water conduits |
| Generators | Reservoir | Surge tank |
| Penstocks | Water rights | Power house |
| Transformers | Lands | Electrical buses |
| | Construction plant | Switching equip. |
| | Station service equip. | |
| | Control equipment | |

It is necessary to divide the third group between the first two groups in accordance with the estimated expenditures that would apply to each group, which leaves the two groups of proportional and independent costs. For the purpose of this discussion the annual costs that do not vary with the changes in kilowatt plant rating are called "base" costs, and the costs which are approximately proportional to the kilowatts are called "proportional" costs. The distinction between proportional first costs and proportional annual costs must be kept in mind. The first costs, which can be divided between proportional and base first costs do not vary directly with the proportional and base yearly costs as the yearly expense of operation and maintenance is considered as part of the base yearly costs. The balance of the base yearly costs are made up of the interest, depreciation, insurance, and taxes on the investment required for the base first costs.

Hydroelectric power stations are designed to exercise a particular function in carrying the system load which is determined by the stream flow characteristics, useful storage at the hydro site, and the type of system load. Hydro stations can be divided into the following four general classes, and for illustration an example of each class is given.

1. Complete development with complete storage; stations designed to utilize the entire stream flow energy during years of mean or minimum stream flow by means of storage. Chelan and Cushman.

2. Complete development with partial storage; stations that have storage or pondage available for taking care of the daily load variations but not enough to store all of the seasonal variation of stream flow for use when needed during the dry period of the year. Baker River and Long Lake.

3. Partial development; stations that are capable of carrying full load at machine rating continuously. Nisqually and Niagara Falls.

4. Complete development without storage or pondage; stations utilizing as much of the stream flow as is economically possible without storage or pondage with the help of auxiliary power. Rock Island.

By complete development is meant utilizing as much of the potential energy of the stream as is possible with the economical storage and type of load that is available. Each of the above classes is discussed separately.

## COMPLETE HYDRO DEVELOPMENT WITH COMPLETE STORAGE

The first type of project to be discussed is that of plants designed to utilize the entire potential energy of the stream during years of mean or minimum stream flow at any required load factor without wasting water by means of storage. Whether to use, in the analysis, the mean stream flow or the minimum or some stream flow in between is determined by the amount of steam standby on the system that can be used exclusively by that plant in case of water shortage. In the case of storage adequate to meet a number of low water years, the maximum stream flow which would be continuously available as determined by the mass diagram or stream flow hydrographs, is used, augmented by the steam standby. In any case the annual cost of the steam standby must be charged against the hydro project.

As an illustration of this type of development, Fig. 1 shows the yearly operation of a hydro power station by monthly averages. The necessary reserve capacity is not included in the following discussion of this assumed project. The yearly output of 35,000 average kilowatts is assumed to be backed up by enough standby energy to supply the difference between the low water stream flow years and the average energy available as determined by the stream flow records. There is assumed to be sufficient storage in the basin above the dam to store the excess energy that occurs during the months of March, April, May, October, and November to be used during the balance of the year, so that all of the energy in the stream is available to meet the load as determined by the monthly load curve. The amount of generating capacity necessary to meet the yearly peak is determined by the load which has both a seasonal variation in energy requirements and an hourly variation in daily load, the combination of the two determining the yearly load factor. In the illustration in Fig. 1, the monthly load factor is assumed to be 60 per cent for every month so that with the monthly variation in load as shown the yearly load factor would be 47.7 per cent. It is the hourly variation in load throughout the day and not the seasonal variation that has the large effect in determining the yearly load factor on the usual system. The variation of installed generating capacity with load factor is expressed by

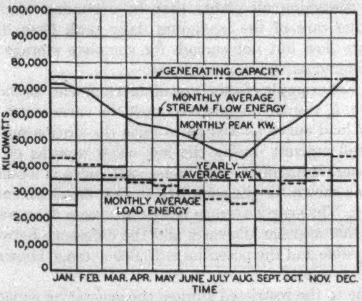

Fig. 1—Yearly Operation by Monthly Averages of a Complete Hydro Development Having Complete Storage

$$L = \frac{H}{K}$$

The following notation is used throughout the discussion.

$A$ = fraction of total annual costs of plant as built that would be necessary to run plant had it been designed for 100 per cent load factor.
$C$ = energy cost per kilowatt hour.
$C'$ = base cost per kilowatt hour.
$D$ = annual demand costs.
$D'$ = annual proportional costs.
$E$ = annual energy costs.
$E'$ = annual base costs.
$F$ = annual demand cost per kilowatt.
$F'$ = annual proportional cost per kilowatt.
$H$ = average kilowatts = kilowatt hours/8,760.
$K$ = peak kilowatts or kilowatt generating capacity.
$L$ = yearly load factor.
$M$ = total cost per kilowatt hour.
$P$ = plant factor.
$T$ = total annual costs.

On this type of development, the energy available in the stream ($H$) is constant so that the required generating capacity is inversely proportional to the load factor. This relation is shown in Fig. 2 for the hydro station in the above illustration. The energy is constant at 35,000 average kilowatts regardless of the load factor, while the required generating capacity for a load factor of 47.7 per cent is 74,000 kilowatts. If the load for the station had a load factor of 100 per cent it would be necessary to have installed only 35,000 kilowatts.

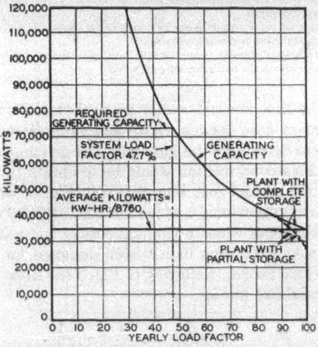

Fig. 2—Variation of Energy Output and Generating Capacity with Load Factor for Complete Hydro Developments Having Storage

The relation between generating capacity and annual station costs is shown in Fig. 3. The total annual costs ($T$) is made up of the base costs ($E'$), and the proportional costs ($D'$). The base costs ($E'$) are constant regardless of the generating capacity while the proportional costs ($D'$) vary directly with the generating capacity. As the energy output is constant and as the generating capacity varies inversely with the load factor, the total cost per kilowatt hour can be expressed by

$$M = \frac{E'}{H\,8760} + \frac{D'}{KL\ 8760}$$

$$M = C' + \frac{F'}{L\,8760}$$

There are two methods of segregating the base and proportional annual costs on an actual project of this type. The first method would be to divide the actual construction cost between base and proportional and from these determine the base and proportional annual costs. The second method would be to obtain the slope of the total annual cost line shown in Fig. 3. which is the annual proportional cost per kilowatt ($F'$), by means of an estimate of what the annual cost of operating the plant would have been had it been designed for a 100 per cent load factor. Referring to Fig. 3 the slope of the total annual cost line is

$$F' = \frac{(T - AT)}{(K - H)} = \frac{T\,(1 - A)}{(1 - P)K}$$

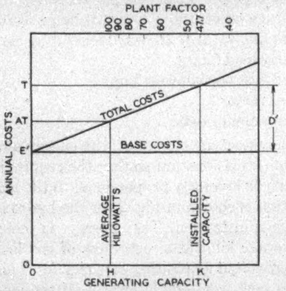

Fig. 3—Variation of the Annual Costs of a Hydro Station with Generating Capacity

$T$ = total annual costs as constructed
$D'$ = annual proportional costs as constructed
$E'$ = annual base costs
$A$ = fraction of total annual costs as constructed necessary to run plant designed for 100 per cent load factor
$K$ = peak kilowatt capacity
$H$ = average kilowatts = kw-hr. output/8,760

The base cost per kilowatt hour is

$$C' = \frac{T\,(A - P)}{\mathrm{H}\ 8760\ (1 - P)}$$

It is evident from the above that the proportional cost per kilowatt ($F'$) is the demand cost of service and that the base cost per kilowatt hour ($C'$) is the energy cost of service. Likewise the annual proportional costs ($D'$) are annual demand costs and the annual base costs ($E'$) are annual energy costs.

Fig. 4 shows the cost per kilowatt hour for different load factors as calculated for the power station referred to in Fig. 1. The base or energy cost of service is constant while the proportional or demand cost of service varies inversely with the load factor.

## Complete Development with Partial Storage

A large proportion of the hydroelectric developments does not have adequate storage to meet the system load without wasting water during the mean or minimum stream flow year and so would come in the classification of partial storage. For the purpose of this discussion all plants that have pondage enough to take care of the maximum daily peak from daily stream flow but not enough for complete storage are considered partial storage plants.

In the example of this type of development, as shown in Fig. 5, storage adequate to meet the variation in the daily load curve as well as to raise the station output a small amount during the low water months of the summer, is assumed. The same load curve is assumed as was shown for the complete storage development in Fig. 1. The yearly average potential stream flow energy is 50,000 average kilowatts and the difference between the usable and the potential is 15,000 average kilowatts which is wasted.

Due to the restricted storage the generating capacity for the plant if designed for 100 per cent load factor would be 27,000 kilowatts instead of 35,000 kilowatts and the energy output would also be cut down. As the generating capacity of the plant is increased from 27,000 kilowatts to 44,000 kilowatts the usable energy output is also increased from 27,000 to 35,000 average kilowatts, and the yearly load factor reaches approximately 80 per cent which is due to the variation in seasonal load and not the variation in the daily load curve. It is necessary to install additional generating capacity to take care of the hourly load variation which does not increase the energy output. It is evident that to increase the energy output above 35,000 average kilowatts with-

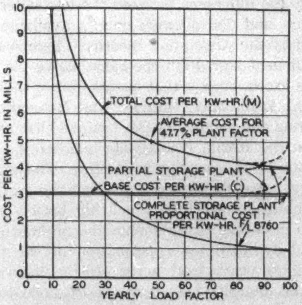

Fig. 4—Power Cost Curves for Complete Hydro Developments Having Storage

out the use of auxiliary power, it would be necessary to increase the load during the period of the year when there is an excess of stream flow, which would be in the nature of secondary power. The variation of energy output and generating capacity is as shown in Fig. 2, and is the same for this assumed development as for the one shown in Fig. 1 for load factors from zero to 80 per cent. Between 80 and 100 per cent load factors the energy available and the generating capacity are less, due to the restriction imposed by the type of site.

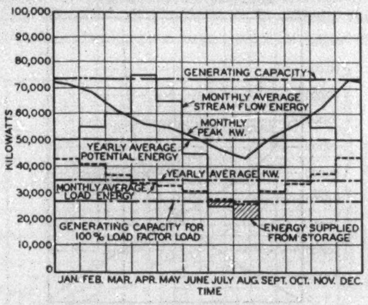

Fig. 5—Yearly Operation by Monthly Averages of a Complete Hydro Development Having Partial Storage

The same power cost equations with correction factors would apply to this type of development as for the development with complete storage. The proportional cost per kilowatt in the case of partial storage developments may be obtained by the second method as outlined for complete storage developments. In this case an estimate of annual expenses is made for operating the plant with generating capacity corresponding to the annual average load as if it were 100 per cent load factor, and the correction factors applied to take care of the decrease in kilowatt hours.

The cost per kilowatt hour curves for the partial storage plant, Fig. 4, are the same as for the complete storage plant as long as the energy output is the same. The base cost per kilowatt hour above 80 per cent load factor is increased by the ratio of the average yearly load divided by the average usable energy, at any given load factor. This in turn increases the total cost per kilowatt hour at those load factors.

### Partial Development

Under most circumstances the hydro plant is designed to utilize as much as is economically possible of the available energy of the stream and so there are very few finished projects that would come within the partial development classification. The Niagara Falls Power stations are outstanding examples of this type of development as the amount of water that can be taken from the river is fixed by treaty between Canada and the United States. The stream flow that is allotted for power purposes is a certain percentage of the minimum flow of the Niagara River. Uncompleted plants that have been designed for complete development of the river later would sometimes come under this classification if the installed capacity is less than the usable potential average kilowatts throughout the period of the investigation of power costs. The characteristic of this type of development is that the plant is capable of furnishing load equal to the installed capacity at 100 per cent load factor.

Fig. 6 shows conditions of stream flow and load for a development of this class. The same load and generating capacity as assumed in the two classes of development, previously discussed, are shown.

There are two ways of looking at this type of project which depends upon the limiting factors that caused the stream to be partially developed. One is that the amount of water that can be taken from the stream is fixed and the other is that the installed generating capacity is fixed. If the amount of water that can be taken from the stream is fixed, the plant output is fixed, and the cost analysis would be the same as for a plant having complete storage. Some plants designed many years ago with a minimum of generating capacity could not have additional generating units added now without rebuilding the entire plant, and until that is done they can be called fixed capacity plants.

With a fixed generating capacity plant, the kilowatt hour output is proportional to the load factor as shown in Fig. 7. The yearly cost of operating the project is fixed so that the cost per kilowatt hour is inversely proportional to the load factor and the following equation would hold. The cost per kilowatt hour is

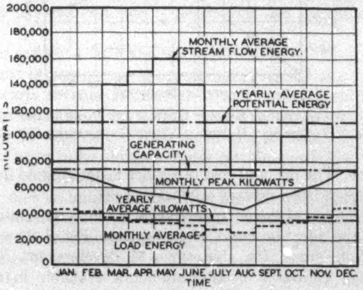

Fig. 6—Yearly Operation by Monthly Averages of a Partial Hydro Development

$$M = \frac{T}{KL\,8760}$$

The cost per kilowatt ($T/K$) is the demand cost of service, so that for this type of project all of the station costs are considered demand costs.

## Complete Development Without Storage or Pondage

A hydro project without storage or pondage cannot usually be used economically without other means of supplying the system load demands during periods of low stream flow. The stream flow fluctuations never follow the load demand of a system supplying the usual type of loads without some pondage so that this type of site could not be developed and used to the best advantage without other means of supplying power.

If the stream is flashy, the plant cannot be relied upon to furnish the power when required, so that its development would be used to supply energy only. As long as the energy can be used on the system the cost per kilowatt-hour would be the same regardless of the load factor and can be expressed by

$$M = \frac{T}{\text{Kw-hr.}} = \frac{T}{H\ 8760}$$

and in this case all station costs are energy costs of service. The demand cost of service is determined from the cost of the necessary auxiliary power.

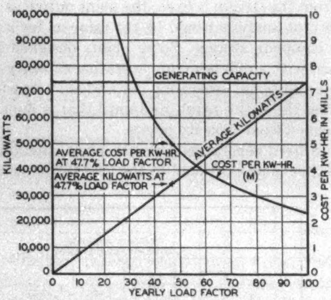

Fig. 7—Variation of Energy Output and Power Cost for a Hydro Development Having a Fixed Generating Capacity

The value of the average kilowatts ($H$) is determined from the duration curve of the stream. Fig. 8 shows a duration curve for this type of development. The average kilowatts or kilowatt-hours available in the stream with different installed generating capacities is also shown in Fig. 8 and is calculated from the duration curve.

The annual costs per kilowatt-hour for the development with different values of installed capacities are shown in Fig. 9. The most economical development would be 60,000 kilowatts providing the night load on the system is great enough to use the entire power from this station. It should be noted that if it were necessary to provide additional demand capacity by steam or more units in other stations in order to use the energy from this type of station, the cost of the additional demand capacity would have to be included with these station costs in determining the economical development.

The above discussion of the four main types of hydroelectric plants could not be construed as a complete discussion, as some stations are constructed for a particular type of load that will only fit in with other plants on the system. A plant may be designed for use during only a portion of the year and other plants may be designed to furnish energy during part of the year and demand capacity during other times of the year. Other plants may be on the dividing line between any two of the above discussed types. Such plants would require special analysis as to the use for which they are intended in accordance with the principles as outlined above.

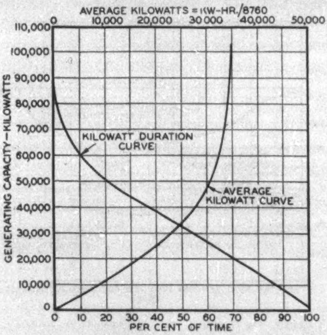

Fig. 8—Duration and Energy Curves for a Hydro Plant Having No Storage or Pondage

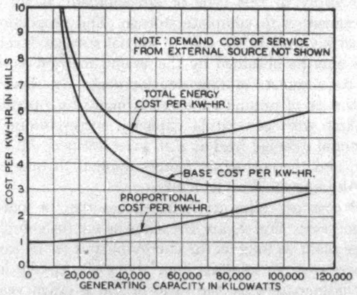

Fig. 9—Energy Cost of Power for a Hydro Plant Having No Storage or Pondage

In the case of transmission lines from the hydro station to the system transmission network, their annual cost should be included with the hydro station annual costs, and they can be analyzed similarly to the station costs.

## III—Average Cost of Hydro Power

The discussion so far has to do with the segregation of hydroelectric power cost into the two components of demand and energy costs for plants delivering energy up to their capacity. This condition is not realized often in practise but the relation between the demand and energy costs, as determined above, is fixed within limits regardless of the loading on the plant.

The usual hydro system that has a growing load can not construct new hydro plants in such a way as to have the system annual expenses increase proportionately as the load increases. As a new plant is added, which requires at the beginning a large outlay for base costs, the yearly expenses increase by a large percentage while the yearly growth in load may be only normal or may be less. Before the plant is loaded up there is likely to be a period of many years in which the annual expenses are practically constant, but as the load increases the cost of power decreases. The length of time to be used in arriving at the average cost of power is determind by the use for which the investigation is made. The annual cost each year is important for operating, while for rate analysis an average cost over a period of years is essential. The immediate past experience of the utility and the future expected conditions as to load growth and the expansion program are essential in determining the average power cost over a period of years, to be used for rate investigation. The number of years to be used in determining this average cost is important as it effects the cost materially. Past experience should be included back as far as a point in the life of the system when the accumulated revenue is equal to the accumulated expenses. How far into the future the period of investigation should extend is determined by the length of time the forecasts of construction program and load growth can be made and still be within the desired accuracy of the investigation.

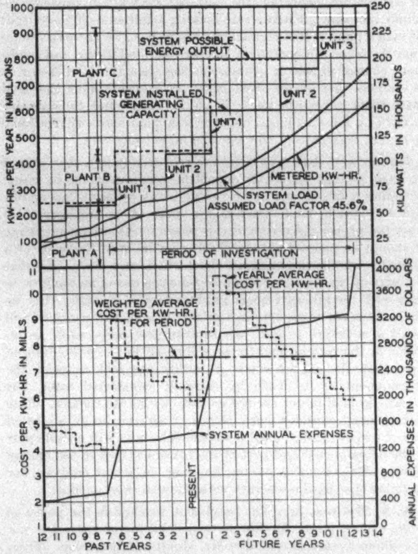

Fig. 10—Load, Capacity, Expenses and Power Cost for a Hydroelectric System Over a Period of Years

As an illustration of the relation between construction program, load growth and average cost of power, the yearly statistics of an assumed system are shown on Fig. 10. The upper diagram shows the growth in load that has occurred in the last twelve years and the expected growth during the next fourteen years. The rate of growth has been approximately 7 per cent in the past and is expected to continue at the same rate in the future. The present load is being carried by the two hydro stations, A and B. The proposed hydro development plant C is expected to take care of the system growth for the next 13 years and the proposed construction program is as shown on the upper diagram.

The system annual expenses are shown on the lower diagram. It is assumed that the accumulated expenses were equal to the accumulated revenue at the time plant B was constructed 6 years ago. The average cost of power for the period of investigation, which extends into the future through the known construction program is weighted to take into consideration the varying yearly average cost per kilowatt hour and increase in load.

It is evident that if the revenue is based on the average cost of power over the period of investigation, that the yearly revenue is insufficient at times to meet the yearly expenses. The utility would have to borrow money to take care of this condition, so that interest would have to be charged under certain conditions for the use of the borrowed money.

By such an analysis of the past and future conditions of the utility some point in the period of investigation can be found that will have a system load and system expenses that will give an average cost of power for the period.

### Summary

In an analysis of electric power costs there are two elements that make up the load; first, the power or kilowatts, and second, the energy or kilowatt hours. It is, of course, impossible to have one without the other and the relation between the two is expressed by the load factor. In the analysis, either the power is assumed to be constant and the energy will vary with the load factor or the energy is assumed to be constant and the power or kilowatts will vary with the load factor. In the analysis of hydroelectric power costs, the energy output of the generating station per year is fixed by the stream flow so that the kilowatts are assumed to vary inversely with the load factor.

The units of cost, in the above analysis of hydroelectric power costs, are so arranged that if the system load factor changed from what it had been when the plant was designed, the annual cost would change to correspond to that of a plant designed and built for the new load factor. If the revenue from all the different loads supplied by the plant is based on the demand and energy costs as derived for the plant, the total revenue received will correspond to the annual expenses of the station as if designed for the plant load factor. Diversity losses, reserve capacity and customer costs must of course be considered in arriving at the annual costs and plant load. The average cost of power over a period of time by the above method is the same as would be found by the method where all station costs are considered demand costs, but the cost per kilowatt hour at load factors above the system load factor is greater than by the demand cost method, but less at load factors below.

One of the principal uses of the analysis is in the economic selection of the method, and the location of generating power, to meet the system load growth, when there are several hydro sites to compare. The analysis is also useful in determining the economic combination of steam and hydro power.

## Discussion

**J. S. Moulton:** There are two principal purposes for which analysis of power costs is required:

1. The comparison of relative costs of various plants or combination of plants which may be selected in constructing or enlarging a power system for the purpose of obtaining the lowest total annual cost.
2. The analysis and apportionment of costs among various classes of load so as to compare the allocated cost of service with the revenue secured from these various classes.

The problem of construction program, the elements which must be considered, and the manner of attack, has been very well covered by a number of authors in the past. Papers by Mr. A. H. Markwart appearing in the *Journal of the Franklin Institute*, August 1927, pages 176-190, and *Electrical West*, September 1930, page 136, are particularly valuable contributions to this subject. In the development of the most economical construction program, it is not necessary to segregate the costs of various projects under consideration into so-called demand and energy components. It is usual to develop costs for a number of different installed capacities and to determine for each of these capacities the cost per kilowatt hour for various load factors. By means of methods described in the above mentioned papers, the most economical combination of steam and hydro may be determined for various load factors. From these data and from known system characteristics, a construction program may be laid out. For any particular system, there are of course many related factors such as partial investments in potential developments, requirements for local supply at some particularly weak point on a transmission network, and many others which must be given consideration.

The division of total generating plant costs between demand costs and energy costs is required for a cost of service analysis. Mr. McCrea's paper, after some discussion of costs, reaches the conclusions that the base cost per kilowatt hour, assuming that a plant could be constructed to operate at 100 per cent load factor, is the energy cost of service, and that the additional cost incurred by reason of less than 100 per cent load factor operation is the demand cost of service. The first of these conclusions is in reality a premise upon which the validity of much of the balance of the paper depends. It is perfectly correct to assume in case of 100 per cent load factor operation that the costs involved can be expressed on a kilowatt hour basis. It is equally correct, however, to assume that they can be expressed on a per kilowatt basis and this is the basis on which power is sometimes sold to high load factor consumers, particularly in the vicinity of Niagara Falls. The desirability of considering base costs as demand costs of service rather than an energy cost of service is illustrated by Fig. 7 of the paper. In this figure it is shown that with a fixed generating capacity installed, if the average kilowatts falls below 100 per cent load factor, the cost per kilowatt hour increases. If such minor items as possible variation in operating expense and maintenance of a hydro plant with change in output are neglected, the cost per kilowatt of capacity remains the same. From a rate making standpoint, if the output of such a plant is sold on a kilowatt hour basis on the assumption that the plant will operate at 100 per cent load factor, and conditions change so that it operates at less than this load factor, it is obvious that at the fixed price per kilowatt hour the total plant costs will not be met. If, on the other hand, the capacity is sold on a kilowatt basis, then the total plant costs will continue to be met regardless of how the load factor may vary.

If rates were fixed purely from a cost standpoint, they should be fixed so that the utility would be reimbursed for its costs, including a fair return on the value of its property, no matter how the system load factor might vary. It is probably aside from the proper discussion of this paper to discuss rate making. It should be pointed out, however, that most of the costs of a hydroelectric development are fixed when once made, and that if a part of these costs is assumed for purposes of an analysis to vary with the kilowatt hours produced when in reality they do not, a decrease in the system load factor from that assumed will result in a failure to meet the total project costs, while an increase in the system load factor will result in the production of more than the project costs. A utility can seek to guide the development of its loads by carefully considered rates, but changes in load factor are not entirely within its control. Rate making must consider many things in addition to an allocated cost of service, and in most instances schedules will include part of the demand cost and part of the consumer cost in the energy charge. This is not a reason, however, in a cost analysis, for assuming that fixed costs vary with kilowatt hour output.

**W. S. McCrea, Jr.:** The conclusion reached in the paper as to the cost of power for 100 per cent load factor operation is a little different than as stated in Mr. Moulton's discussion. True, the base cost per kilowatt hour is the energy cost of service, but in addition to the base cost per kilowatt hour, there is a proportional cost per kilowatt even at 100 per cent load factor, which would be the demand cost of service. This is shown in Fig. 4 of the paper. The energy cost of service at 100 per cent load factor is shown as over three mills per kilowatt hour and the demand cost of service is less than one mill per kilowatt hour. The total cost of service is the energy cost plus the demand cost of service and is four mills per kilowatt hour at 100 per cent load factor. The demand cost of service if expressed in units of cost per kilowatt would have the same value at any load factor.

If the load factor of a given load is known or could be assumed, it is perfectly correct to express the total cost as either cost per kilowatt or cost per kilowatt hour; or some combination of the two. The question which the paper attempted to answer is how much the total cost would be at different load factors. The method of solving the problem was to determine the variation of construction costs with generating capacity and from this the variation of the annual costs of the plant with the plant factor.

The units of cost in this analysis are so arranged that if the system load factor changed from what it had been when the plant was designed, the annual cost would change to correspond to that of a plant designed and built for the new load factor. In other words, the total cost of power at 100 per cent load factor is the same as if the plant were built to deliver all of its available energy at 100 per cent plant factor.

The fallacy of considering all hydro station annual costs in the nature of demand costs is due to the fact that the amount of energy available is limited by the stream flow, which, in the economically developed plant, is considerably less than if the energy output were limited by the generating capacity as is the case in a steam plant. The results obtained by the two methods for the cost of power at different load factors are very different. The total cost of service by either method is the same at the system load factor, but the cost at load factors above the system load factor is greater by the above analysis than by the demand cost method, but less at load factors below.

It is interesting to note the effect on the economical combination of steam and hydro power of the above method of analysis as against the demand cost method. If we assume the cost of steam and hydro to be the same at the system load factor, the cost of hydro power will usually be greater than steam at the high load factors by the above method of hydro cost analysis, and lower than steam at the low load factors. If the demand cost method were used the results would be just the opposite.

The economical combination of steam and hydro under the above conditions will result in the hydro station being designed with generating capacity enough to take the larger portion of the peak load and the steam station designed for the continuous or high load factor load. The combination of the two may result in an average cost of power lower than either hydro or steam alone.

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# The Reading Company's Philadelphia Suburban Electrification

G. I. WRIGHT*
Member, A.I.E.E.

THE electrification of the Reading Suburban Service in the vicinity of Philadelphia was authorized October 25, 1928, and was placed in operation July 26, 1931. The lines now under electric operation include 65 route miles and 157 track miles which will be increased by January 1, 1933 to 87 route miles and 203 track miles. These lines, as shown on the map, (Fig. 1) consist of six branches and cover all the suburban territory north of Philadelphia between the Schuylkill and Delaware Rivers.

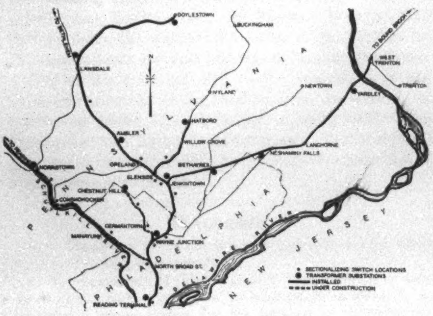
TO BETHLEHEM
DOYLESTOWN
BUCKINGHAM
LANSDALE
N
IVYLAND
NEWTOWN
TO BOUND BROOK
WEST TRENTON
TRENTON
YARDLEY
HATBORO
AMBLER
WILLOW GROVE
LANGHORNE
NESHAMINY FALLS
NORRISTOWN
ORELAND
BETHAYRES
GLENSIDE
JENKINTOWN
CHESTNUT HILL
CONSHOHOCKEN
GERMANTOWN
MANAYUNK
WAYNE JUNCTION
NORTH BROAD ST.
READING TERMINAL
PENNSYLVANIA
PHILADELPHIA
SCHUYLKILL RIVER
DELAWARE RIVER
NEW JERSEY
SECTIONALIZING SWITCH LOCATIONS
TRANSFORMER SUBSTATIONS
INSTALLED
UNDER CONSTRUCTION

FIG. 1—MAP OF SUBURBAN ZONE

Steam operation in this territory has been in service for many years, the Reading being one of the oldest railroads in this country. In the last ten years, however, it has met severe competition from private automobiles, buses, a new subway, and the Pennsylvania Railroad electrified lines, and this has resulted in serious loss of traffic and revenue to the railroad.

The Reading Company was faced with two alternatives, either to continue steam operation, where the only means of cutting cost of operation was to reduce the number of trains, thus further impairing the service and resulting in additional losses of traffic, or to provide a modern superior electrified service, which in addition to other advantages, would materially reduce the operating cost per train mile. It was felt that this would justify the operation of more frequent trains, which with a 20 per cent increase in schedule speeds, greater cleanliness and more attractive equipment, would attract an increased traffic.

In the general design of the electrification and the choice of system and of transmission voltages, it was necessary to give careful consideration to future electrification plans for the system as a whole. It will be noted from a reference to the map of the Reading Company's system (Fig. 2) that the suburban electrification lies within a circle, with its center at Jenkintown, and a radius of 20 miles. It will also be noted that with the same center, a circle with a radius of 80 miles, takes in the Reading Company's lines to Reading and Pottsville; to Bethlehem, to Jersey City (C.R.R. of N.J.); also the Reading and Central Railroad of New Jersey lines in New Jersey, and the Jersey Central's main line from Jersey City to Mauch Chunk. Incidentally, this area also includes the main line of the Lehigh Valley and the D.L.&W. in the same territory; the Baltimore & Ohio, from the Susquehanna River to Philadelphia, the P.R.R. from the Susquehanna to New York and its main line from Lancaster to Philadelphia. There is probably a larger amount of railroad traffic in this area than in any similar area in the world.

It was desired to provide satisfactorily and economically for the suburban electrification in the smaller area and at the same time arrange the initial electrification so that it could be amplified and extended some time in the future to take care of the larger territory.

The single-phase 25-cycle system of electrification was adopted as fulfilling these requirements and at the same time had the advantage of being standard with the system used by the Pennsylvania Railroad in the electric operation of its Philadelphia Suburban service and its electrification from Washington to New York, now under construction.

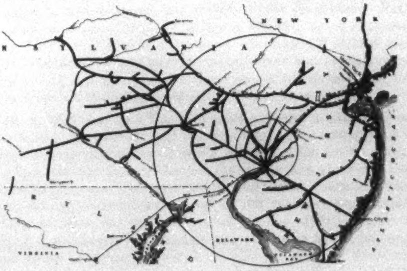
NEW YORK
PENNSYLVANIA
NEW JERSEY
MARYLAND
DELAWARE
VIRGINIA
DELAWARE BAY
ATLANTIC OCEAN

FIG. 2—MAP OF READING SYSTEM

## POWER SUPPLY AND SUBSTATIONS

It was decided to purchase power and the Philadelphia Electric Company installed a frequency changer station at Wayne Junction adjacent to the Reading Company's main substation. A 3-wire distribution system having 12,000 volts between trolley and rail, 24,000 volts between feeder and rail and 36,000 volts between feeder and trolley wire was adopted to transmit the power to the railroad's nine autotransformer substations whose locations are shown on the map. These substations are all designed on a unit basis and consist of one, two or three 2,000-kw. autotransformers and are designed so that as loads increase in the future, these transformers can be moved to outlying points and replaced with 4,000-kw. transformers without any other change to the substations.

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*Chief Elec. Engr., Reading Co., Philadelphia, Pa.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

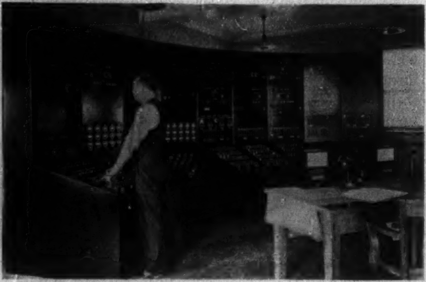

Fig. 3—Supervisory Control Desk—Power Dispatcher's Office

Provision is made for the addition of duplicate single-phase, 66-kv. transmission lines to parallel this 3-wire system. Electrification beyond the initial territory can be carried out by using either a 2- or a 3-wire distribution system fed from one or more outlying points through suitable step-down transformers. This arrangement permits tapping the 66-kv. lines at any desired intermediate points to augment the 3-wire system through so-called "three-winding" transformers.

All substations and switching stations are non-attended and are operated by supervisory control. Details of the power contract, power supply system, substations, and supervisory control, are described in the articles listed in the bibliography and in the interests of brevity, will, therefore be omitted from this paper.

## CATENARY STRUCTURES AND FOUNDATIONS

*General.* The majority of the catenary structures are composed of steel H-section columns and crossbeams which are rigidly connected by knee braces to form self-supporting portal structures.

This type of construction for electrification structures has the following advantages.

1. Low cost of steel per pound.
2. Ease of detailed design and simplicity of shop details. These were made in the railroad's drawing room which saved time and expense.
3. Ease, speed and low cost of fabrication.
4. Simplicity of construction with resulting good appearance.
5. Ease of painting with resulting economical maintenance.
6. The H-section has greater strength in one direction than the other and in this way can be used to take care of all the varying load conditions which arise.

In the five-mile section between Reading Terminal and Wayne Junction there are four or more tracks on an elevated structure. Due to restricted right-of-way it was necessary to carry the transmission circuits on masts instead of on the catenary columns. This necessitated the use of fabricated trusses instead of H-section crossbeams.

These masts were located so that there would be adequate clearance between the wires and any present or future buildings on the properties adjoining the right-of-way.

In outlying sections the structures have H-section columns and H-section beams. However, in cases where the crossbeam spans five or more tracks, channel type beams were used. These beams are composed of two channels laced top and bottom and placed with webs vertical and bolted to the flanges of the columns.

For single-track lines self-supporting columns with brackets for supporting the catenary are used on tangent track. On curves the same arrangement is used with the exception that the columns are back guyed.

Fig. 4—Outdoor Type Frequency Changer

At the outer face of many overhead bridges, which generally were so low as to make it necessary to grade the contact system down to pass under them, a 5-in. standard I-beam was supported by means of brackets. This I-beam in turn carried post type insulators to which were attached the contact system messengers.

On the faces of these overhead bridges it was necessary to provide protective screens so that the contact system passing underneath would be inaccessible to persons on the bridge.

*Signal Bridges.* At signal locations, in sections where there were three or more tracks, the color light signals were placed on the catenary structures. Instead of providing special and heavier structures at such points, the only modifications to accommodate signals were the addition of walkways, signal supports and platforms to the standard catenary structures. The beam type of structure, however, was changed from H-section beam to channel beam in the cases where signals are carried. On trusses the walkways and signal supports, etc., were easily attached by means of J-bolts.

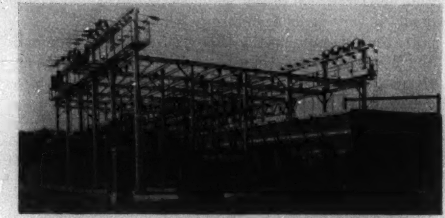

FIG. 5—TYPICAL TRANSFORMER SUBSTATION

*Foundations.* Reinforced concrete foundations of 1-2-4 mix were used for the structure columns. In these, bolts were provided to secure the columns to the foundations.

In many locations within the limits of Philadelphia, it was necessary to design special foundations, the outlines and dimensions of which were largely dictated by adjacent walls, buildings and other structures which existed prior to electrification. These special cases presented many unusual and somewhat difficult problems in design and construction.

The foundations are of two general gravity types, *i. e.*; one providing column fixity both parallel and normal to track, the other giving fixity only in a plane parallel to track. The latter type which was in the majority was very economical both in materials and labor. Due to its narrow width it did not require shoring of adjacent tracks.

In the construction of the foundations, steel panel forms were used. These had a templet at top to hold the foundation bolts securely in their proper position while the concrete was poured and hardening. These forms which were used many times over, were found to be very economical and will continue to be used on future construction.

When hard rock was found at a structure site either a side bearing type of foundation or a type with ragged and wedged foundation bolts grouted into the rock was used. The grouted foundation bolts were used only in solid rock and in such instances the concrete piers were cast around them after grouting.

*Design.* All structures were designed on the basis of standard Class B loading, *i. e.*; ½-in. ice with 8 lb. per sq. ft. wind on wires and 12 lb. per sq. ft. wind on flat surfaces. Also alternate loadings of 20 lb. per sq. ft. on bare wire and 30 lb. per sq. ft. on flat surfaces.

Broken wire loads of 1,000 lb. on column or of 2,000

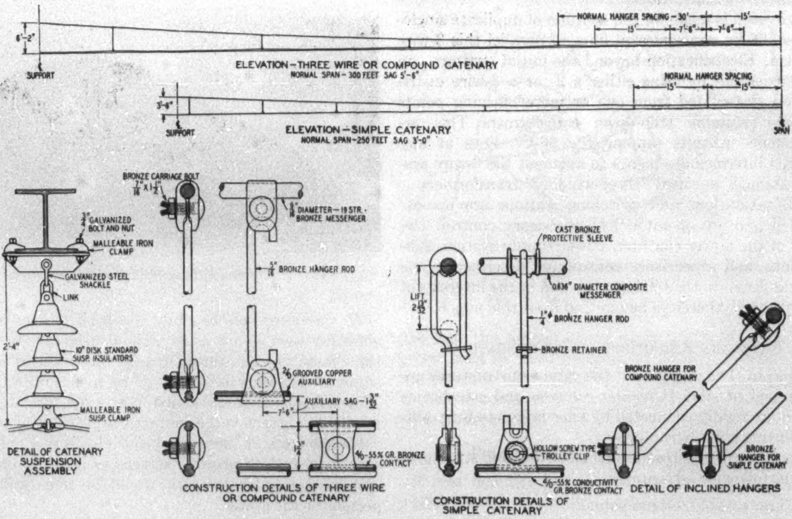

FIG. 6—TYPICAL CATENARY DETAILS

ELEVATION—THREE WIRE OR COMPOUND CATENARY
NORMAL SPAN—300 FEET SAG 5'-6"

ELEVATION—SIMPLE CATENARY
NORMAL SPAN—250 FEET SAG 3'-0"

DETAIL OF CATENARY SUSPENSION ASSEMBLY

CONSTRUCTION DETAILS OF THREE WIRE OR COMPOUND CATENARY

CONSTRUCTION DETAILS OF SIMPLE CATENARY

DETAIL OF INCLINED HANGERS

NORMAL HANGER SPACING—30'
15'
15'
7'-6"
7'-6"
6'-2"
SUPPORT
NORMAL HANGER SPACING
15'
15'
3'-6"
SUPPORT
SPAN
3/4" GALVANIZED BOLT AND NUT
MALLEABLE IRON CLAMP
GALVANIZED STEEL SHACKLE
LINK
2'-4"
10" DISK STANDARD SUSP. INSULATORS
MALLEABLE IRON SUSP. CLAMP
BRONZE CARRIAGE BOLT 7/16" X 1 1/2"
9/16" DIAMETER—19 STR. BRONZE MESSENGER
5/16" BRONZE HANGER ROD
2/0 GROOVED COPPER AUXILIARY
AUXILIARY SAG—1 3/32"
7'-6"
1 3/4"
4/0-55% GR. BRONZE CONTACT
CAST BRONZE PROTECTIVE SLEEVE
0.836" DIAMETER COMPOSITE MESSENGER
LIFT 2 13/32"
1/4" ϕ BRONZE HANGER ROD
BRONZE RETAINER
HOLLOW SCREW TYPE TROLLEY CLIP
4/0-55% CONDUCTIVITY GR. BRONZE CONTACT
BRONZE HANGER FOR COMPOUND CATENARY
BRONZE HANGER FOR SIMPLE CATENARY

lb. on beam were also used. Under the above loadings a maximum fiber stress in steel of 25,000 lb. per sq. in. was allowed in net section.

Reinforcing steel and concrete is stressed to 20,000 and 800 lb. per sq. in., respectively.

Soil pressures of 4,000 lb. per sq. ft. on cinders and 5,000 lb. on earth was allowed.

## DESIGN OF TRANSMISSION LINES AND CATENARY SYSTEM

*Transmission Line.* Bearing in mind the possibility of future "through" electrification to New York, Bethlehem and Reading, provision has been made on the main line catenary structures for the installation of a double-circuit 66,000-volt transmission line. At present the only transmission lines carried are the 24,000-volt feeders or "balance wires" for the three-wire system. On single-track branches, only one of these feeders is used, and on two and four track sections of the railroad, two feeders are installed. All catenary columns are connected together by a ground wire, which is clamped to the pole cap with a special fitting. The ground wires serve manifold purposes; namely, to protect against lightning, to ground the structures, to assist the trolley rail circuit as regards conductivity, to reduce inductive interference and to prevent excessive deflection of the structures in case of a broken transmission or catenary wire. Following the usual practise in railroad electrification, all lines have been heavily insulated. On the 12,000-volt catenary lines, three standard 10-in. suspension units are used in series, and on the 24,000-volt feeders, four units are used. It is proposed to install six units at each suspension point on the 66,000-volt circuits, and all clearances have been made sufficient to accommodate this insulation.

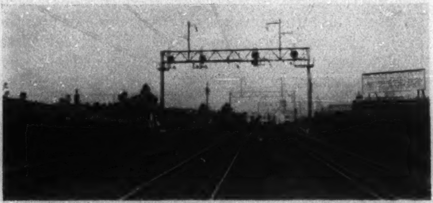
FIG. 7—TYPICAL 4-TRACK SECTION COMPOUND CATENARY

*Catenary System.* From Reading Terminal in Philadelphia to West Trenton on the New York line, the catenary system is of the conventional compound three-wire inclined type. The messenger is a 9/16-in. diameter bronze cable, the auxiliary is a 2/0 grooved copper wire, and the contact is a 4/0 bronze wire. The catenary supports for this type of construction are 300 ft. apart on tangent tracks and wind steadies are placed at every structure on tangent except where shelter is provided by adjacent high buildings, etc.

On all other electrified tracks, simple two-wire inclined catenary is used comprising a 0.636-in. diameter composite bronze and copper messenger and a 4/0-grooved bronze contact wire suspended on tangent track from the messenger by lifting loop hangers. Tangent structure spacing is 250 ft. and no steadies are used on the contact wire. This is the first installation of long span steel structure simple catenary in this country and its use has resulted in simplicity and ease of erection and maintenance, and superior quality of current collection. The simplicity and advantages of the air gaps used with this type of catenary are also very gratifying.

In the table below are shown the different wires used on the Reading electrification.

All catenary and transmission lines were designed to take a stress well below the elastic limit when loaded with ½-in. radial coating of ice at 0 deg. fahr. The variation in alinement of the inclined catenary due to changes in temperature was calculated prior to erection, and where it appeared that excessive lateral movement would occur, steadies were placed on the contact wire. It was found that the greatest movement occurs on the compound catenary on curves where the hanger slope is about 45 degrees.

The hangers, clips, steadies, etc., are all bronze of a composition highly resistant to corrosion. In compound catenary, the hangers are clipped both to the main messenger and auxiliary messenger on tangent track, the hangers alternating with clips which fasten the contact wire to the auxiliary. On the simple catenary, loop hangers are used on tangent track, a protecting sleeve being placed over the messenger at each point to eliminate any possibility of wear. In every second span of simple catenary on tangent a feeder jumper of flexible cable joins the contact wire to the messenger; the

| Size wire | Purpose | Material | Conductivity cm. | Weight lb. per ft. | Ultimate strength | Normal tension | Maximum working tension |
|---|---|---|---|---|---|---|---|
| 9/16-in. diameter | Messenger | Bronze stranded | 34,000 | 0.744 | 19,750 | 3,820 | 7,500 |
| 0.636-in. diameter | Messenger | Composition bronze and copper | 211,600 | 0.935 | 19,100 | 4,340 | 7,675 |
| 4/0 | Contact | Bronze (grooved) | 116,400 | 0.641 | 10,200 | 2,500<br>3,000 | 4,170<br>4,670 |
| 2/0 | Auxiliary | Copper (grooved) | 133,000 | 0.403 | 5,220 | 1,200 | 2,200 |
| 7/16-in. diameter | Messenger (yards) | Bronze stranded | 20,900 | 0.457 | 12,150 | 2,490 | 4,830 |
| 2/0 | Feeder and ground wire | Copper stranded | 133,000 | 0.411 | 6,270 | 830 | 2,350 |
| 4/0 | Feeder and transmission | Copper stranded | 211,600 | 0.653 | 9,970 | 1,320 | 3,140 |
| No. 1 | Signal circuit | Copper stranded | 83,700 | 0.255 | 3,740 | 520 | 1,820 |

loop hangers, therefore, are required to carry only a negligibly small current. The inclined hangers on curves are identical on both the simple and compound catenary. They comprise a 3/8-in. diameter rod, upset to 7/16-in. at the lower end, and provided with a shoulder to receive the contact wire clips.

The car storage yards and the Reading Terminal are wired with chord catenary, consisting of a 7/16-in. messenger and a 4/0 contact wire. In all wired cross-overs, and at sectioning points in the main line, air breaks are installed. Wood stick insulators are used only where it was not possible to use air breaks.

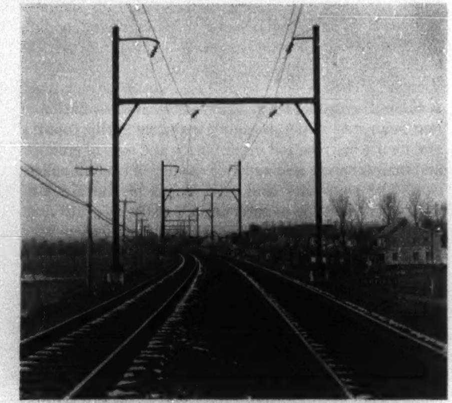

FIG. 8—TYPICAL 2-TRACK SECTION SIMPLE CATENARY

Where highway bridges pass over the tracks, the catenary is carried on rigid post type insulators erected on brackets on each side of the bridge. A minimum clearance of 6 in. from the messenger to ground is permitted at certain points, but the desired standard clearance is 9 in. or more. The standard contact wire height is 22 ft. and in approaching overhead bridges, the gradient in the contact wire is kept down to 0.5 per cent relative to the track.

Prior to erection of the contact line, all stringing tensions and hanger lengths were worked out, so that field adjustments were reduced to a minimum. Where inclined catenary is used, the stringing tension on curves is less than on tangent; to take care of this, the messenger was snubbed on every curve during tensioning; then when the contact wire load was added, the messenger assumed its proper tension on both tangent and curved track, and the snubs were removed.

## RAIL RETURN SYSTEM

*Traction Bonds.* The standard rail section of the Reading System is a 130 lb. head-free type. The joint is one developed for use with this rail and the joint and rail have a cross section not particularly adapted to the application of all types of bonds as the bead on the joint projects a considerably greater distance than is the case with the usual rail joint.

The traction bonds selected for installation on this system are of No. 1 A.W.G. gas weld 8-in. straight type.

*Impedance Bonds.* On all main line tracks the rails are a part of the 100-cycle a-c. track circuit. In order that the rail return may be continuous, impedance bonds having a continuous rating of 100 amperes per rail are provided around the insulated joints which permit the traction power to flow but offer high impedance to the flow of signal current.

*Special Bonding.* In order effectively to ground each structure, all structures wherever possible are tied together by means of ground wires, the ground wires being bonded to rail through impedance bonds, usually at the end of every other track section so as to provide maximum broken rail protection.

Cross bonds or bonds connecting together the rails of all bonded tracks, are installed at frequent intervals. Insulated 2/0 cable is used for these bonds and, as in all cases wherever there is any possibility of maintenance of way forces disturbing the installation, a covering of fiber impregnated planking is installed directly over the cable and the whole covered with earth.

### MULTIPLE UNIT CARS

| Type of car | In service | Under construction | Total | Seating capacity | Baggage space | RPO space |
|---|---|---|---|---|---|---|
| Motor | 61 | 28 | 89 | 86 | 0 | 0 |
| Motor | 7 | 2 | 9 | 62 | 17 ft. 1 in. | 0 |
| Motor | 2 | 0 | 2 | 38 | 16 ft. 8½ in. | 17 ft. 1 in. |
| Trailer | 20 | 0 | 20 | 84 | 0 | 0 |
|  | 90 | 30 | 120 | Total |  |  |

The trailer cars which were converted from steam cars are used only in rush hour trains and in the ratio of one trailer car to three or more motor cars. Due to the fact that these rush hour trains are largely express runs, the schedules and motor heating are not greatly effected by this method of operation. All trailers are equipped with electric heaters, bus connectors, cab signals and a control cab at both ends, so as to give maximum flexibility of operation.

Each motor car is a complete unit, equipped with motors, storage battery, air compressor, cab signals, and a control cab at each end. On the 30 motor cars under construction the cab signal equipment is being omitted, but provision is being made for its installation when needed.

A careful study was made of the use of aluminum alloys and the economies involved due to the resultant weight savings. Alternate bids were obtained from the car builder on the use of aluminum in the various parts and resulted in a saving of 6,640 lb. per car. The estimated annual saving in power cost due to this weight reduction was considerably more than the interest on the additional investment. The trucks, side-sheets, underframing and all stress carrying members are of steel construction.

The seating arrangement consists of 37 cross seats spaced 33½ in. from center to center to provide ample leg room, and three longitudinal seats, each seating four people.

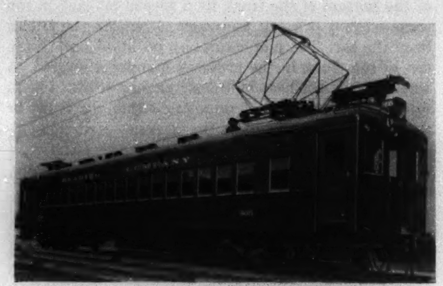

Fig. 9—Multiple Unit Car

The interior of the car is painted three-tone gray, striped in blue and gold. The hardware fixtures, baggage racks and light fixtures are of a sanded nickel finish, giving the cars a clean, bright appearance. Brass window sash is used which eliminates sticking and adds to the appearance of the car.

There are no signal or emergency cords passing through the car, the signals being electrically operated by push buttons. The emergency cord is located in the vestibules, but is accessible from the inside of the car. There are two push buttons for the conductor's signal buzzer, located in the interior of the car, one over each vestibule end door, and one under each corner post of the car. The latter are provided so that the conductor can stand on the station platform and signal the motorman to start, just before he boards the train, thus saving a little time at each stop.

*Motors and Control.* Due to the short runs and severe grades it was desirable to obtain as large a traction motor as possible and still meet the space and other design limitations. Therefore, new designs were developed by each manufacturer and used on the cars. These new designs produced a motor with a one hour rating of 300 hp. and a continuous rating of 240 hp. The improvement over prior designs is brought about by using a larger number of poles, permitting a low flux density, which in turn produces better commutation. In addition, the weight per horsepower is considerably less than on previous motors, while exceptionally high values of efficiency and power factor have been made possible.

An accelerating rate of 1.25 mi. per hr. per sec. is obtained in service with a normal voltage of 11,000 at pantograph and with full seated load, resulting in a car weight of approximately 70 tons. This weight is divided 60 per cent on the motor truck and 40 per cent on the trailer truck, resulting in a low adhesion of 10.4 per cent and consequently very little wheel slipping.

This accelerating rate is the highest yet attained on a-c. equipment, and even though it is less than generally used on d-c. multiple unit equipment it results in a higher schedule speed in a service in which the average length of run is over 0.8 miles. For example, although it takes 24 seconds for a car to reach 30 mi. per hr. it only takes 60 seconds to reach 50 mi. per hr. Another example of the sustained horsepower of these motors is the fact that a 2-car train has a balancing speed of 56 mi. per hr. on a grade of 1.13 per cent. On level tangent track the balancing speed is between 75 and 80 mi. per hr., depending on the length of train; however, the equipment is restricted to a maximum speed of 72 mi. per hr.

The main controller is of the automatic accelerating type located under the car and remotely controlled through a 32-volt circuit from a master controller in the cab. The master controller has the dead-man's release which is further equipped with a foot pedal to hold it in position so that the motorman can have both hands free if desired.

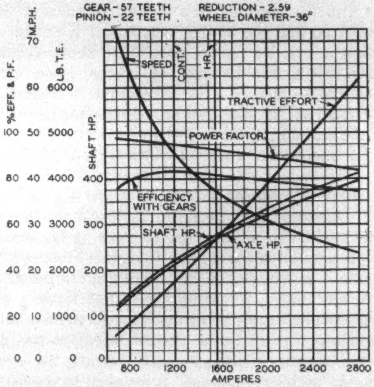

Fig. 10—Motor Characteristic Curves

170/340-volt, single-phase, 25-cycle railway motor. Characteristic curves on 170 volts, 25 cycles

*Trucks.* Eighty cars are equipped with Taylor flexible trucks and 20 with Commonwealth trucks. The Taylor truck has been used before on freight cars and on some experimental installations of passenger cars and locomotive tenders but this is the first time it has been used on electric cars. Its advantages are, greater flexibility and lighter weight.

## NEW DEVELOPMENTS

One outstanding development of the car is the bus connector. This connector makes it possible to connect all pantographs together, thus providing power on all cars when only one or two pantographs are in service. It is expected that the use of this device will show considerable savings in pantograph shoe and trolley wear. It has already shown its value in making it possible to continue a trip with power on *all cars* after pantographs have been damaged on several of the cars in the train.

A magnetic door latch has been developed and installed on the body end doors of the cars. This latch holds the doors open during the time a train is coasting to a stop and standing in a station but automatically releases the doors upon the starting of the train. When released, the doors are closed gently by an ordinary air cushion door check. This device insures the doors being open a minimum length of time, thus reducing drafts on the passengers and conserving heat in the cars.

Double thermostat control of the electric heaters is used, one thermostat being set at 50 deg. fahr. and the other at 65 deg. fahr. These thermostats are so connected that when the engineman has his controller plug in the master controller the 65 deg. thermostat is connected and when he leaves his cab, as during short lay-overs in the terminal, the 65 deg. thermostat is disconnected and the 50 deg. thermostat is cut in. This makes it possible for the cars to be kept moderately warm during the lay-over. Of course, when the car goes into storage and the pantograph is lowered, the heat is all cut off. Switches are also provided for cutting off the heat during warm weather.

The motorman is also provided with a "train heat" switch which enables him to change all thermostats in the train from the 65 deg. to the 50 deg. setting at will. Operating rules require him to cut off this train heat switch ten minutes before reaching his terminal, unless the equipment is going to remain in service. This results in a considerable saving in heating power cost.

A new design of ventilating system is used which insures sufficient air being delivered to the motors and transformer at all times. Special attention was given to the cleaning of the air and to keeping the velocity low. A "no blower cut-out" is installed to prevent the operation of a car in case of a failure of the ventilating system.

## INTERCHANGEABILITY OF APPARATUS

Although the motor and control equipment was furnished by three different manufacturers, and two different types of trucks were used, it was possible by careful design, to build all the cars from one set of drawings and use one schedule of hangers. The traction motors and air brake rigging are so designed that it is possible to interchange the two makes of trucks.

Very careful attention was given to the arrangement of apparatus on the underside of the car so as to simplify inspection and maintenance.

The flexible connection through which the air passes to ventilate the motors is designed so that it automatically disconnects itself when the motor is removed and then automatically goes into place when the motor is replaced.

A spring motor nose suspension is used which can readily be removed and the motor can be dropped out of the bottom of the truck by a special pit jack in the shop without it being necessary to remove the trucks from the car. The motor can also be lifted out of the top of the truck in the ordinary manner if desired. A wheel pit has also been built into the shop so that wheels can be dropped without removing either the truck or the motors. This eliminates the necessity of disconnecting the motor leads when changing wheels. These pit jacks can also be used to remove the transformer, compressor and other apparatus.

## STORAGE, INSPECTION AND REPAIR FACILITIES

The storage yard is located at Wayne Junction and is designed to accommodate 86 cars at present and 160 ultimately, keeping one track open as a run-around track.

The new shop is located near the center of the storage yard and is provided with five tracks, three for light inspection and two for heavy repairs. All tracks are long enough to accommodate 4 cars and are arranged so that the cars can be routed progressively into one end of the shop and out of the other. This gives the shop a capacity sufficient to maintain over 200 cars. Room is provided for an extension of 125 ft. on the heavy repair bay for the maintenance of future electric locomotives.

## OTHER IMPROVEMENT WORK DONE CONCURRENTLY WITH ELECTRIFICATION

As in all terminal electrifications, extensive improvements were made concurrently with electrification. These consisted of elimination of grade crossings; obtaining additional clearances at points where overhead bridges or other obstructions did not give sufficient clearance for installation of the overhead wires; building new suburban car storage yards at outlying points; a new car storage yard for storing cars at Wayne Junction during the middle of the day; the change and modernization of the signal system in the electrification territory and the placing in cable of communication circuits. In certain territory where right-of-way was restricted, underground ducts were provided for signal and communication cables. Nine new stations were also built at various points in the suburban territory. The cost of all these associated improvements exceeded the cost of the electrification construction proper including rolling stock.

## INDUCTIVE COORDINATION

It was realized that electric operation of the railroad would necessitate coordination of the electrification and communication facilities, both belonging to the railroad and those of commercial companies, therefore, the railroad's plans were from the beginning discussed with representatives of the telephone and telegraph companies, and this feature was kept in mind during the design of the electrification. A series of cooperative tests was made before the start of electric operation.

From results of over a year of operation there has been no trouble due to inductive disturbances in either the railroad's communication facilities, or those of other companies.

### Construction Features of the Work

The installation of the work in its entirety, with the exception of buildings for car shop and substations, was done by the railroad's construction forces organized for the purpose and under the supervision of the electrical department. The construction features of such an installation are complex and expensive, and made difficult due to the necessity for maintaining traffic at all times without delays. After surveys were made and plans issued to the field forces, the first step was the installation of foundations for catenary structures. Because of congested right-of-way, particularly between Reading Terminal and Wayne Junction, where the railroad is on an elevated structure, and where in many cases the center of the outside tracks is only seven feet from the right-of-way line, the installation of foundations was particularly difficult and expensive. It was necessary to go to extensive shoring of the tracks in order to maintain traffic, this feature for this five miles of railroad costing $40,000 alone. The concrete for the foundations was all mixed and poured from concrete mixing plants installed on cars and operated in work trains. Water was supplied to the mixer from tank cars insulated against cold and heated in winter with steam from the engine. Approximately 35,000 yards of concrete was used in the work.

Steel structures were all erected by means of a derrick car, purchased for the purpose, which could be operated on one track without obstructing traffic on adjacent tracks. Steel was shipped from the fabricator in cars loaded in the order in which it was to be installed; thus eliminating rehandling on the job.

Transmission wires were strung by means of teams of horses in the customary manner for power lines. The messenger, auxiliary and trolley cables were strung by using reel cars from which the cables were led out through temporary sheaves attached to the bottom of the suspension insulator strings. All wires, fittings, etc., were installed from tower cars by means of work trains, and all wire and fittings were designed, assembled, and marked for the span or the structure where they were to be installed and delivered to proper location. This scheme resulted in minimizing the time required in the field, which is absolutely essential due to the high cost of work train service and the interference with traffic by the work trains.

The substation steel and apparatus were installed in the customary manner. The supervisory control equipment was installed by the substation construction forces.

Concurrently with the above the bonds were being installed, wire crossings eliminated or altered, signals and communication changes made, additional yards installed, tree trimming attended to, etc., etc.

As soon as power was available and a section was completed, everything was thoroughly tested out with particular reference to obtaining proper selectivity on the circuit breakers, and actual short circuits to ground were placed on every circuit of the network. The system of relaying was new and some adjustment of relays was found necessary.

Such a construction program requires close cooperation from the purchasing, stores, signal, telegraph, engineering and motive power departments and particularly the operating department. During a considerable part of the time, there were as many as 20 work trains in use on the work.

Several months before the start of operation, the training of the steam enginemen who were to operate the new equipment; the inspectors and shop forces who were to maintain it, and the power dispatching and electrification maintenance forces, was started. Instructions in operating and safety rules were issued, and all electric trains on all branches were placed in operation simultaneously on the morning of July 26, 1931.

### Results

Electric operation has now been in effect over a year. In spite of speeding up of schedules by 20 per cent and an increase in trains and train miles of approximately 100 per cent, the cost of operation is substantially lower than was the case for the service in the same territory by steam. A continual loss in traffic has been changed into an appreciable increase, and as a result of this showing, the railroad management recently authorized the electrification of the suburban service on its Norristown Branch from Philadelphia to Norristown. This service, along with the Chestnut Hill Branch, will go into operation about January 1st 1933.

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## Discussion

**J. S. Moulton:** There are three matters covered in Mr. Wright's paper, in addition to the technical description of the electrification, which deserve emphasis.

The first of these is the problem confronting all railways whether local, interurban or steam. The increasing competition from other forms of transportation has severely reduced both passenger and freight traffic of the railroads. All roads have reduced operating expenses drastically in an effort to offset reduced revenues. With a large part of the total costs tied up in permanent capital, and, therefore, not susceptible to reduction, there is a limit beyond which operating cuts are not effective. Stimulation of traffic and modification of the basic character of the system, are additional methods of endeavoring to maintain profitable operations. An experiment with fares as a means of stimulating street car travel which at the time of writing is being tried at Bakersfield, California, may be of interest. The existing tariff which has been in effect for several years is a 10c. cash fare, 7 tokens for 50c., or a $1.00 weekly transferable pass. The system has not been earning more than pocket operating expenses for the last year, but before deciding upon abandonment, a drastic experiment is being tried. For a two-month period free passage is being given between the hours of 9:30 a. m. and 3:30 p. m., Sundays and holidays excluded. Following this period, a 5c. fare for all hours will be tried out for a period of three months. After that, it is planned to restore the former schedules if experience in the meantime does not indicate the wisdom of some other tariff. The merchants are featuring the free ride privilege with their advertising. While it is too early to tell what the effect of the experiment will be, the total number of passengers during the first month of this free ride period has been over three times the number for the preceding month, and the business of the merchants has improved.

The second feature of Mr. Wright's paper describes the use of visual cab signals in place of more expensive full automatic control. According to Mr. Wright, the use of cab signals has been fully justified by the absence of accidents. While safety is of course the primary requirement, it is important to keep both investment and operating expenses at a minimum. How much better it would be if the railroads with their vast store of operating experience, and with new methods constantly being developed, could be free from the unelastic requirements now prescribed by regulatory bodies, the experience of which is frequently theoretical rather than practical.

The third point of general interest relates to the cooperative manner in which the rate for power was worked out between the Reading Company, and the Philadelphia Electric Company, the rate providing that after the railroad load reaches a certain fixed amount that the charge will be based upon cost of service including a fair return on the property required to serve the railroad. One of the reasons that an electric utility can give service more cheaply than isolated plants is that through serving a diversity of loads, its generating capacity can be operated at a higher load factor than could a number of separate and isolated plants. The agreement to compute the rate on cost of service is in line with the modern tendency toward giving greater weight to the cost elements of service and further indicates the increasingly cooperative spirit between different kinds of utilities. The arrangement between the railroad and the electric utility for joint use of right-of-way, and for service at cost, is a step in the right direction toward greater coordination of utility services from which the public will be the greatest benefactor.

**A. J. Schoch:** The complete suburban electrification of the Reading Company was engineered and installed by Mr. Wright and his staff. While established practises were adhered to in general, they did not hesitate to depart from such practise when their objective necessitated doing so. Operation to date has proved the wisdom of such departures. The most striking example was the installation of simple two-wire catenary over a large part of the electrified tracks. In this country it has been universal practise to install some form of compound catenary for all main line and suburban electrifications. Of course, the low conductivity required with the high-voltage, single-phase system makes the simple two-wire catenary quite attractive. This form of catenary is far superior from the standpoint of simplicity and ease of erection and maintenance.

Furthermore, experience has shown that the quality of current collection is also better. Experience to date has resulted in the decision to install this type of catenary on the Norristown and Chestnut Hill lines which are now being electrified. The results obtained will, no doubt, lead to the adoption of simple catenary for future heavy traction electrifications.

A very careful study was made of the use of aluminum alloys in both the electrical equipment and the car body. However, its application was limited to non-stress carrying members. Even with this limitation, the Reading car ranks first, from the standpoint of weight per seat or weight per continuous horsepower, among modern high voltage multiple unit cars either alternating current or direct current.

Greater effort and study were undoubtedly given to the location and arrangement of equipment underneath the car than was ever attempted heretofore. This not only simplified the original installation but has made the job of inspecting and maintaining the equipment much easier. Furthermore, in spite of equipment being supplied by three different manufacturers complete interchangeability of apparatus was secured.

A number of novel features were introduced on the car. The most outstanding of these was the high-voltage bus line connecter. This connecter gives many operating advantages and the results have been very successful; the coupler itself requiring practically no maintenance.

Due to severe grades and short runs encountered on the Reading system, the service is unusually severe. The equipments designed to meet this service are capable of accelerating the cars at 1.25 miles per hour per second up to a speed of 30 miles per hour and have a balancing speed in excess of 70 miles per hour. Consequently, in average suburban service these cars are capable of making the highest schedule speed of any suburban cars in this country.

# Electrical Operation on the Cascade Division of The Great Northern Railway

BY J. B. COX*

Associate, A.I.E.E.

THE electrification of the Great Northern Railway main line between Skykomish and Wenatchee, 73 route miles, has been quite fully described in a number of articles published in technical journals during the past three years, rendering it unnecessary to repeat a detailed description of the installation here. The electrification was carried out in conjunction with the building of a new tunnel 7.79 miles long and a relocation of approximately 17 route miles of troublesome track and other minor improvements, aggregating an expenditure of approximately $25,500,000. All these improvements were placed in operation at about the same time so that there has been no opportunity to make a direct and segregated comparison of operating expenses which would indicate definitely the advantages of each improvement separately.

The completion of this new tunnel was the second undertaking of that nature in the history of the Great Northern Railway's route across the precipitous Cascade range. The original route, which was placed in operation in 1893, went over the range through Stevens Pass at an elevation of 4,059 feet. It was possible to keep the maximum grade at a limit of 2.2 per cent up to elevation 3,382 feet on the eastern slope, and to elevation of 3,126 feet on the western slope. These points were approximately 2.7 miles apart by direct line through the mountain or 4.5 miles over the Pass.

A tunnel between these points was considered at the time but it would have cost more and taken much longer to build, two very important items in those days, so the line was built through the Pass. This was done by increasing the ruling grade to 4 per cent and resorting to an eight point switchback, involving approximately 12 miles of track.

As had been foreseen, this switchback became the proverbial bottle-neck of the line and with the natural increase of traffic, its capacity was soon reached. This was particularly so during the winter months when there was apt to be an aggregate fall of any where from 50 to 100 feet of snow, and at a rate as high as 8 to 10 inches per hour at times.

To overcome these difficulties and to improve the service, the construction of a 2.63-mile tunnel was begun in 1897 and placed in operation in 1900. This tunnel ran in a perfectly straight line at a constant grade of 1.695 per cent eastbound, cut out the entire switchback and eliminated 2,332 degrees of curvature and all grades in excess of 2.2 per cent. This improvement shortened the route approximately 9 miles which reduced the running time of all trains about two hours with a corresponding decrease in operating expenses.

With a further increase in traffic the ventilation of this tunnel became so unsatisfactory with the operation of coal burning steam locomotives that the tunnel and tracks at each end were electrified. The three-phase system was selected for this installation largely because of its ready adaptation to regenerative braking and was the first and only application of this system in America, as well as the first regenerative braking on a steam railroad. This installation and the necessity for same were fully described in a paper by Dr. Cary T. Hutchinson,† the consulting engineer.

The electrical operation of this tunnel was begun in July 1909 and the three-phase equipment satisfactorily met the original requirements and was continued in service until March 1927 when it was replaced by the present system.

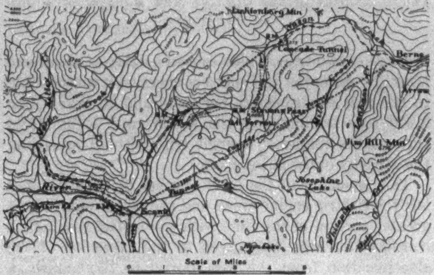

FIG. 1—TOPOGRAPHICAL MAP SHOWING LOCATION OF THE OLD AND NEW ROUTES

The only notable modification of the equipment was the installation of the necessary wiring and switches for arranging for a concatenated connection of the traction motors which provided for a running speed of 7½ miles per hour in addition to the 15 miles per hour originally selected. This was done in the latter part of 1923 when the division point was removed from Leavenworth to Wenatchee (Appleyard) which increased the length of the freight run from 109.3 miles to approximately 132 miles, and it was desired to take the entire train through the tunnel at a single trip instead of in two trips as was necessary at a speed of 15 miles per hour, owing to the limited capacity of the Tumwater power plant.

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*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

†*The Electric System of the Great Northern Railway at Cascade Tunnel*, A.I.E.E. TRANS., 1909, Vol. 38, p. 1281.

At the beginning of the electrical operation, the freight trains did not exceed 1,600 tons trailing so that three of the 115-ton electric units were used to take this train with the road steam locomotives, equivalent to about 450 additional trailing tons when being hauled at 15 mi. per hr., through the tunnel at one trip. With a gradual increase of the train weights it had been found necessary to cut the heavier trains and take them through in two trips, which caused a delay of about one hour. By using the half-speed connection it was possible to use four electric units per train and to take up to 2,200 tons trailing and the steam road locomotives through the tunnel at a single trip, without exceeding the capacity of the power plant.

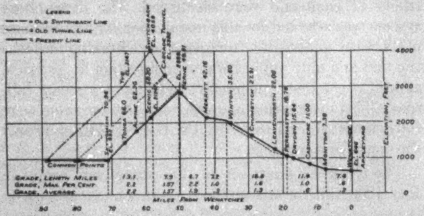

Fig. 2—Profile of the Old and New Routes, Skykomish to Wenatchee

This lessening of the total number of trips per day left the electric engine crews and the power plant idle a greater portion of the time with the logical result that consideration was soon given to the extension of the electrification from the west portal to Skykomish, a distance of approximately 21 miles, so that the electric units might be used to replace the steam locomotives used in the helper service on the 2.2 per cent grade up the west slope. A study of this plan indicated that quite a saving in operating expenses should result in addition to some saving in time as there would be practically no increase for electrical operating cost since the extended service would only increase the load factor without adding greatly to the crew hours paid for and the necessity for the stop at the west portal of the tunnel would be avoided. In the consideration of this extension it was realized that a new tunnel would undoubtedly be constructed within a few years, involving a new route which would result in the abandonment of at least nine miles of this proposed extension as well as the old tunnel electrification and that the expenditure for the extension should be kept at a minimum and that any additional electrical locomotives required should be capable of use on any desired change of route.

In the extended service the electric locomotives would operate as helpers to the regular steam road locomotives up the practically continuous 2.2 per cent grade for the 21 miles to the western portal of the old tunnel, at the entrance to which steam would be shut off, and the electric locomotives would have to take the train up the 1.695 per cent grade through the tunnel. The weight of trains would vary from 400 tons in the case of the lighter passenger trains to 2,500 tons for the heavier freight trains.

The available capacity at the power house was approximately 4,000 kw.

The constant speed characteristics of the three-phase locomotives with only two operating speeds were not best suited to meet these conditions and these, with the complications in the contact system owing to the necessity for the two overhead wires, made it unlikely that this system would be chosen in case the electrification should be extended beyond the mountain section.

The motor-generator type of locomotive which permitted of a combination of the most desirable features of the single-phase system and the d-c. system with which the speed might be varied to any degree necessary to conform to either the weight of train or available power or both, thus being well adapted to operation as helper to a steam locomotive, was chosen as being best suited to meet all the existing conditions. For the extension outlined, one double-unit class 1−D−1+1−D−1 motor-generator locomotive was originally ordered.

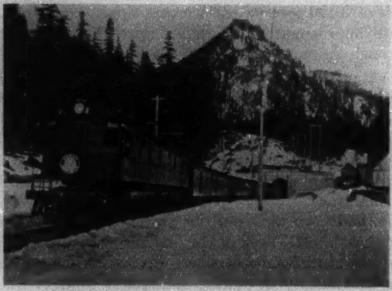

Fig. 3—Locomotive and Train Leaving Western End of New Cascade Tunnel

260-ton, 11,000-volt, single-phase, motor-generator type—Great Northern Railway

The three-phase generators at the power house were of liberal design, having sufficient excess capacity over the waterwheels to permit of their operation single-phase.

A few months after the equipment for this extension had been ordered and before it had been completed a decision was reached to construct a new tunnel 7.79 miles in length. The new route would leave the main line at Scenic on the west slope and join it again at Berne on the east slope, thus substituting 9.99 miles of new route for 17.67 miles of the old route with advantages as indicated in the following table of comparisons:

| | Old line | New line | Advantages of new line |
|---|---|---|---|
| Length in miles | 17.67 | 9.99 | 7.68 |
| Maximum curve degree | 10.00 | 6.00 | |
| Total curvature degree | 2,128 | 187 | 1,941 |
| Maximum grade | 2.2 | 2.2 | |
| Tunnel grade | 1.695 | 1.565 | |
| Summit elevation ft | 3,382 | 2,881 | 501 |
| Total rise westward | 546 | 45 | 501 |
| Total fall westward | 1,325 | 824 | 501 |
| Total length of snow shed-miles | 6.04 | | 6.04 |
| Total length bridges miles | 0.23 | 0.04 | 0.19 |
| Total length tunnels miles | 3.66 | 7.79 | |

The new line remained below the elevation of heaviest snow fall and traversed a route less subject to drifts and slides. A re-location of the line had also been surveyed between Winton and Peshastin which avoided some troublesome line in the Tumwater Canyon and reduced the maximum grade from 2.2 per cent to 1.6 per cent, the maximum curve from 10 degrees to 3 degrees and the total curvature 1,286 degrees and shortened the line about 1¼ miles.

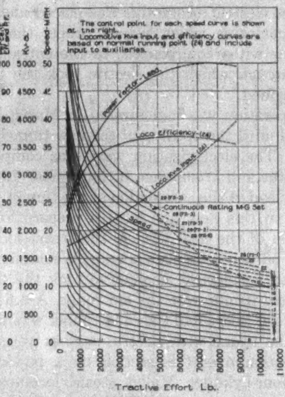

FIG. 4—CHARACTERISTIC CURVE OF $1-C+C-1$ LOCOMOTIVE MOTORING

Locomotive characteristics 10,500 volts, 25 cycles

With these revisions of line in view and a definite decision to electrify the entire line between Skykomish and Wenatchee and to leave off the steam locomotives between these points, the character of the service was so changed as to make it desirable to consider some revision in the additional motive power that would be required for the extended service.

The 42 miles between Merritt and Wenatchee over the new route would safely permit speeds of 50 miles per hour whereas the line between Skykomish and Cascade Tunnel did not permit speeds in excess of 30 to 35 miles per hour and the new locomotive had been designed accordingly with a maximum safe speed of 40 miles per hour. With only 73 route miles electrified requiring so few locomotives, it was desirable to have all locomotives interchangeable between the passenger and the freight service and that any locomotive be capable of being operated in the same train with any other locomotive. The regular passenger trains operated over the line varied from 8 to 12 cars, aggregating from 700 to 1,000 trailing tons and the freight trains would ordinarily range between 2,500 and 4,000 tons trailing.

Fig. 2 shows a condensed profile of the present line and of the old lines. The ruling grade in each direction is 2.2 per cent, 10.5 miles of which is practically continuous, between Skykomish and the west portal of the new tunnel and 5 miles between Merritt and the east portal.

The grades range from 0.2 to 2.2 per cent, the average up grade for the line being approximately 1.29 per cent.

To meet these new conditions, a class 1–C+C–1 locomotive unit was proposed, the weight, etc., of which is given in the following table in comparison with the double unit locomotive supplied for the extension from Cascade Tunnel to Skykomish:

| Classification | 1–C+C–1 | 1–D–1+1D–1 |
|---|---|---|
| Total weight | 539,000 | 715,400 |
| Weight on drivers | 426,200 | 550,000 |
| No. of driving axles | 6 | 8 |
| Weight per driving axle | 71,030 | 68,750 |
| Weight on guiding axles | 112,800 | 165,400 |
| Weight per guiding axle | 56,400 | 41,350 |
| Length over couplers | 73 ft. 9 in. | 94 ft. 4 in. |
| Total wheel base | 58 ft. 8 in. | 78 ft. 11 in. |
| Rigid wheel base | 15 ft. 4 in. | 16 ft. 9 in. |
| Height over pantograph down | 15 ft. 3 in. | 15 ft. 10 in. |
| Number of traction motors | 6 | 8 |
| Tractive effort continuous rating | 60,500 | 88,500 |
| Tractive effort 30 per cent adhesion | 127,860 | 165,000 |
| Speed at continuous rating | 18.6 | 15.5 |
| Maximum safe speed mi. per hr | 50 | 40 |
| Number ordered | 8 | 5 |
| Secondary voltage transformer | 2,300 | 1,100 |

The 1–C+C–1 locomotives, designed particularly for the mixed service over the new line, will handle a 1,000-ton trailing train at 18.5 miles per hour on the 2.2 per cent grade and up to about 45 mi. per hr. on the 0.2 per cent, or averaging over the entire up grade portion about 28.6 mi. per hr., the average output of the motors being approximately 2,100 kw. or a rated load factor of 84 per cent. On the down grades the speed is limited to a maximum of 50 mi. per hr.

The regenerative features of the locomotive provide satisfactory control of the speed on the varying down grades to meet any conditions imposed by curvature, track conditions, or schedule requirements, ranging over the first 24 running points of the power controller, for each of which point graduated variations are possible through the 16 points on the braking controller, which regulates the traction motor field current.

Figs. 4 and 5 give the motoring and braking characteristics of this locomotive. Fig. 6 shows a schematic diagram of the control connections.

Two of the 1−D+D−1 locomotives were placed in the Skykomish-Cascade tunnel service in March 1927, two in the fall of 1928 and one early in 1929. The five locomotives of this class having been in service the equivalent of about 23 locomotive years.

Two of the 1−C+C−1 locomotives were placed in the Skykomish-Cascade tunnel service in September 1927, two others a year later and four were ordered in October 1929, nine months after the complete electrification had been placed in operation. These locomotives have now been in service about two years so that the eight units of this class have been in service the equivalent of 25 locomotive years.

Of this grand total of 48 locomotive years, approximately nine years were in the service between Skykomish and Cascade Tunnel as originally planned. This service consisted of helping the regular steam locomotive up the 2.2 per cent grade to the entrance of the tunnel, through which the grade was reduced to 1.695 per cent, making it possible to shut off the steam while in the tunnel.

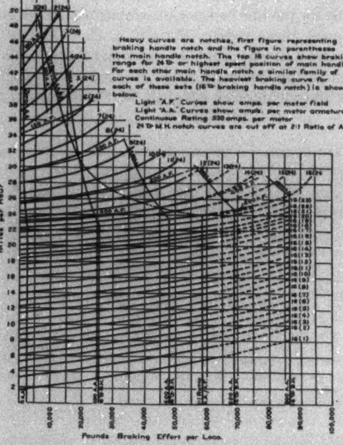

FIG. 5—CHARACTERISTIC CURVE OF $1-C+C-1$ LOCOMOTIVE BRAKING

The freight trains during 1927-1928, ranging from 2,500 to 3,500 tons trailing, were brought to Skykomish by two steam locomotives. Here, the rear steam locomotive was dropped off and replaced by two electric locomotives, one ahead of the steam road engine and one in the rear of the train. In the beginning, the rear locomotive was put at the extreme end of the trains but later it was found to be safer operation to place the rear unit about half to two-thirds back the length of the train. In the case of very long trains, with a powerful locomotive at each end, if for any reason the head engineer finds it necessary to stop suddenly and makes an emergency application of the brakes or should an air hose burst near the front end, the locomotive and cars so far away do not respond so quickly to the application and the front of the train is apt to stop before the brakes on the locomotive and cars at the rear have become sufficiently effective to prevent the momentum of the heavy locomotive from buckling the train at some weak spot, since the operator on the rear locomotive often has no warning of what is happening in time to shut off power until it is too late to prevent the damage. In descending grades by regenerative braking, it is also much safer and easier to have the two locomotives near together.

These heavy freight trains were taken from Skykomish to Cascade tunnel, 25 miles, in 1¾ hours whereas with steam operation from four to five hours were usually required. In the case of the passenger trains, one electric locomotive was placed ahead of the steam locomotive which helped propel the train, in accordance with requirements, to the entrance of the tunnel through which the electric took the train and engine unaided.

This operation was inaugurated in March 1927 and continued until the opening of the new tunnel January 12, 1929. The electrification work was completed between Berne and Wenatchee in November 1928, three months ahead of the completion of the tunnel. In order to break in this new line and to prepare for the inauguration of the new service, the steam locomotives were left off the passenger train at Wenatchee, and at Skykomish an electric locomotive took the trains between these points over the old route. A 4.5-mile section between Berne and Cascade tunnel was not wired so that the trains with electric engines were taken in each direction over this section by a powerful class 2-8-8-2, four-cylinder Mallet steam locomotive. The freight trains were operated as before until the opening of the new tunnel when the new schedule for electric service went into full effect.

Wenatchee being a division point, all engines and crews both passenger and freight are changed on arrival there. On arrival of all trains at Skykomish from the west, the engine crews shift from the steam locomotives to the electric and continue the trip to Wenatchee. All westbound engine crews similarly transfer from the electric to the steam locomotives and continue to Seattle.

The first ten days of electrical operation over the new route through the new tunnel was without serious incident, but about January 20th the weather began to grow cold and a day or so later the thermometer indicated 15 deg. below zero fahr. on the east side of the mountain and varied between zero and this point for several days and was accompanied by dry snow which drifted badly. On January 22nd the transformer on a locomotive in freight service burned out. This was followed by three other burn-outs of transformers and

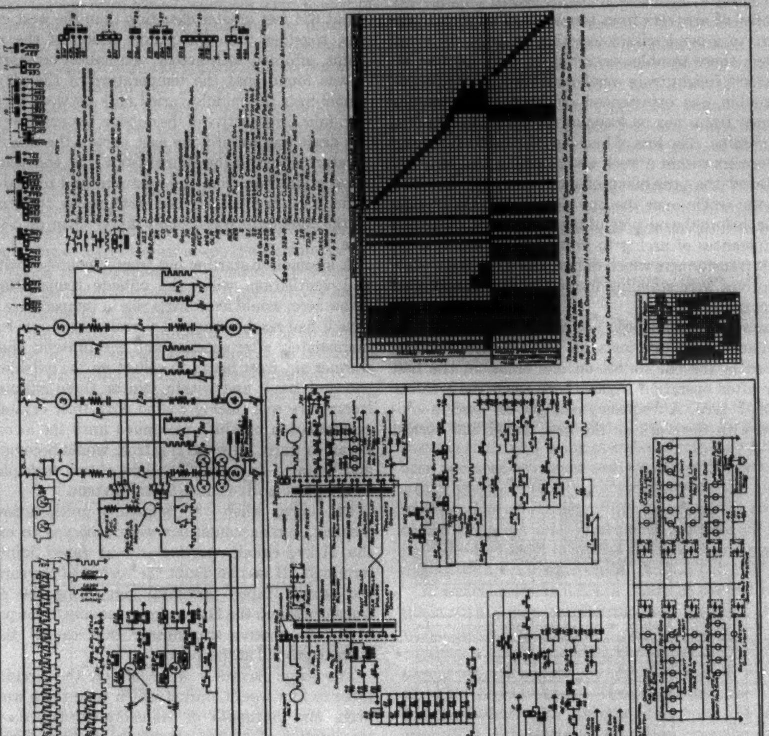

FIG. 6—SCHEMATIC WIRING DIAGRAM OF 1–*C*+*C*–1 LOCOMOTIVE

a number of arcovers from terminals of current transformers to ground within less than a week. In every instance, these troubles occurred on a locomotive attached to a freight train westbound through the tunnel. No trouble was experienced on locomotives hauling passenger trains nor on locomotives eastbound hauling freight trains. The loss of four out of a total of 14 main transformers within a week was alarming and seriously threatened the possibility of continuing the handling of all the traffic over the line electrically. On two occasions, before the opening of the new tunnel, there had been instances of arcing to ground from terminals of current transformers which did no serious damage while locomotives were standing inside the new tunnel near the east portal.

A transformer had been lost and an arcover at current transformer terminals on two locomotives had occurred in the old tunnel on one occasion, the first winter after operation began there when the weather was below zero. A frequency changer set used in connection with the work on the new tunnel had burned out and other disturbances on the line had occurred on the same day, so it was thought these troubles were due to surges.

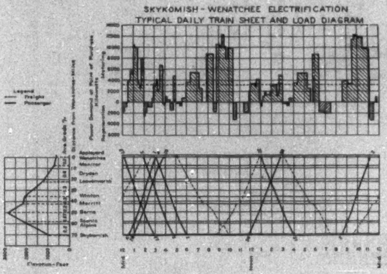

FIG. 7—TYPICAL DAILY TRAIN SHEET AND LOAD DIAGRAM

Additional insulation was installed on the terminals and to the transformers where the trouble seemed to have originated and there had been no further instances of this trouble in the old tunnel. When the arcovers began to occur in the new tunnel, steps were taken immediately to have three surge recorders placed on the trolley circuit, one at each end of the tunnel and one midway between. A fourth recorder was placed on a locomotive running over the entire line. These had just been installed when the sub-zero weather arrived and the more serious troubles began.

It had been noted that when the temperature outside the tunnel was below freezing, there were some signs of condensation on the outside of the locomotive cab and on the inside near the air intakes and that this condensation increased as the temperature outside approached zero. The east end of the new tunnel is at about 634 feet greater elevation than the west end and this, together with the piston action of the moving trains, afforded satisfactory ventilation ordinarily but it was found that the temperature of the air in the tunnel near the middle varied only between 50 and 65 deg. fahr. irrespective of the outside temperature. Since the draft was toward the east portal, the rise in temperature entering the tunnel from that end was much more rapid than from the west end and to add to the difficulties, the outside temperature on the east side of the mountain was usually lower than on the west side.

A locomotive starting out from Wenatchee with normal ventilation, when the outside temperature was below zero, would show little rise in temperature by the time it had reached the east portal of the tunnel so that immediately after entering and encountering the much warmer air, frost began to collect on the outside of the cab and truck and within two or three minutes, the locomotive was thickly coated with frost crystals, the accumulation of which continued until the locomotive began to warm up when this frost would become liquid and begin to drop off. The same action took place inside the locomotive but to a lesser extent.

At times, when the moisture precipitation was greatest, corona conditions were observed to exist on the 11-kv. circuit, particularly at taped joints and terminals. It was no doubt the corona at the surface of the heavily taped terminals connecting the current transformers on the 11-kv. circuit leading to the primary of the locomotive transformer that caused the arcovers to ground at this point.

The surge recorders were left on the circuit from three to four weeks, during which time there were arcovers and burnouts of transformers but a careful examination of all the records failed to indicate that there had been any surges registered, above two times normal. This being well within the limits ordinarily expected from necessary switching operations, surges were eliminated from responsibility for the trouble.

The moisture condition was aggravated by the large volume of air drawn into the locomotive by the blowers for cooling the electrical equipment. The outside temperature east of the tunnel varies from around 100 deg. fahr. in summer to 15 deg. below zero during winter, making it necessary to supply in the hottest weather about 40,000 cu. ft. of air per minute.

Experiences with other locomotives requiring much less ventilating air had indicated conclusively that dangerous quantities of moisture would be carried inside the locomotives by this large volume of air, during rain or snow storms, and in order to protect the electrical equipment from this danger the louvers for the 1−C+C−1 locomotives had been provided at the factory with adjustable shutters by means of which the openings for air intake could be varied from fully open to completely closed.

In order to insure proper ventilation of the apparatus when the louvers were closed, dampers were placed in the outlets for the air from the apparatus, by means of which the air could be directed back into the locomotive for re-circulation through the apparatus, thus replacing the moisture-bearing air from the outside.

While it had not been foreseen that there would be so great a variation between the temperature outside and inside the tunnel as to cause serious trouble, these provisions for closing the louvers and re-circulation of the inside air were readily applicable to the overcoming of this unexpected danger.

By closing the louvers and adjusting the dampers at the beginning of a trip the air inside the locomotive was easily raised to a temperature so nearly approaching that of the air inside the tunnel as to prevent any harmful precipitation of moisture.

When the weather conditions are such as to require the closing of the louvers the temperature outside is never at a maximum so that the re-circulation of the inside air does not cause excessive heating of the apparatus.

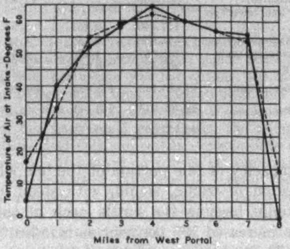

FIG. 8—DIAGRAM SHOWING TEMPERATURE VARIATIONS IN THE NEW CASCADE TUNNEL IN NEAR ZERO WEATHER

— West bound trip Jan. 30, 1929
— — — East bound trip Jan. 31, 1929

The electric locomotives have since operated through three winters without any trouble from condensation.

Fig. 8 which shows the variations of the temperature of the air inside the new tunnel would seem to explain why the failures were confined to locomotives on west bound trains since the rate of rise is considerably more rapid when entering from the east portal. The failures were mostly on locomotives attached to freight trains which had taken siding and waited some time before entering the tunnel, thus allowing the apparatus to cool down below normal.

This trouble from condensation is the only serious difficulty that has been experienced in the operation of the electrified line.

The motor-generator type of locomotive is well adapted to the conditions of the service where the freight trains may vary from 2,500 to 5,000 tons trailing and it is desirable to limit the maximum power demand to the most economical point, since the multiplicity of the running speeds makes it practical to select speeds that will keep the power demand at any desired point, with varying train weights on irregular grades.

The first cost of the locomotive and its weight per horsepower is apt to be greater and its overall efficiency somewhat less than other types. The maintenance cost of these locomotives during the three years 1928-9-30 has been 28.66 cents per locomotive mile, or 13.65 cents per 100 tons on drivers.

A comparison of these costs with those of three other electrified roads using locomotives with regenerative braking on heavy grades in similar service is as follows:

| | Locomotive miles | Per locomotive mile | Per 100 tons on drivers |
|---|---|---|---|
| Chicago, Milwaukee, St. P. & P. | 7,939,539 | 14.20c. | 6.92c. |
| Norfolk & Western | 1,520,608 | 46.82 | 17.60 |
| Virginian | 1,562,574 | 48.49 | 12.26 |
| Great Northern | 937,492 | 28.66 | 13.65 |

A direct comparison of operating expenses between steam and electric operation is impossible for the reason that the route now being operated electrically has never been operated by steam and consequently there are no steam records precisely comparable with the electrical records. The shortening of the route and the reduction of the elevation and consequent lessening of the lift by the new tunnel have had an important part in reducing the operating expenses.

However, early in 1920, a study of the old line was made with a view to electrification for the purpose of which operating data and costs were carefully prepared covering 12 months ending September 30, 1919 for the steam operation between Skykomish and Wenatchee through the old tunnel. These data are still available for comparison with corresponding costs covering the year 1929 with electrical operation over the new line. Table I shows a direct comparison of those items of operating expense which are vitally affected by electrical operation for the two years mentioned.

The total cost of the improvements involved in production of the new line and the electrification was in round numbers approximately $25,500,000 made up as follows:

| | |
|---|---|
| 7.9 miles tunnel complete | $14,000,000 |
| 17.0 miles | 5,000,000 |
| 73 miles electrification | 6,500,000 |
| Total | $25,500,000 |

The segregated costs of the electrification were approximately as shown in Table II.

In reviewing the study made in 1920 relative to the electrification of the old line for comparison with the present electrification, it was interesting to find an estimate made at that time of the cost of the proposed electrification of the 80 miles of line between Leavenworth and Gold Bar which was practically the same distance as Wenatchee to Skykomish through the old

TABLE I—COMPARISON OF OPERATING COSTS FOR ITEMS VITALLY AFFECTED BY ELECTRIFICATION

| | Steam | Electric | Difference<br>Amount | Per cent of steam |
|---|---|---|---|---|
| Route miles | 80 | 73 | 7 | 8.8 |
| Locomotive miles | 767,151 | 406,910 | 360,241 | 47.0 |
| 1,000 ton miles | 485,000 | 408,108 | 76,892 | 15.8 |
| Train miles | 607,000 | 292,930 | 314,070 | 51.7 |
| Costs— | | | | |
| Enginemen | $276,597 | $ 80,049 | $196,548 | 71.0 |
| Trainmen | 175,819 | 77,413 | 98,406 | 56.0 |
| Fuel or power | 659,850 | 269,298 | 390,552 | 59.2 |
| Locomotive repairs | 243,114 | 109,085 | 134,029 | 55.1 |
| Enginehouse | 67,260 | 22,885 | 44,375 | 66.0 |
| Lubricants | 3,325 | 5,525 | +2,200 | 66.2 |
| Supplies | 3,414 | 1,643 | 1,771 | 51.9 |
| Water | 1,308 | | 1,308 | 100.0 |
| Substations | 5,543 | 5,995 | + 452 | 8.2 |
| Distribution | 3,411 | 41,917 | +38,506 | 1128,9 |
| Total | $1,439,641 | $613,810 | $825,831 | 57.3 |
| Average cost per 1,000 ton miles | 2.968 | 1.504 | 1.464 | 49.3 |
| Average cost per train mile | 2.372 | 2.095 | 0.277 | 11.7 |
| Average tons per train freight | 1,882 | 3,021 | 1,139 | 60.5 |
| Average tons per train passenger | 494 | 568 | 74 | 15.0 |
| Average road time freight | 13.4 | 5.5 | 7.9 | 59.0 |
| Average road time passenger | 4.1 | 2.8 | 1.3 | 31.7 |
| Average mi. per hr. freight | 6.0 | 12.9 | 6.9 | 115.0 |
| Average mi. per hr. passenger | 19.4 | 25.5 | 6.1 | 31.4 |

PROPORTIONED BETWEEN FREIGHT AND PASSENGER

| | Steam | | Electric | |
|---|---|---|---|---|
| | Freight | Passenger | Freight | Passenger |
| Locomotive miles | 466,428 | 300,723 | 199,806 | 207,104 |
| Train miles | 207,286 | 399,720 | 98,478 | 194,452 |
| 1,000 ton miles | 390,000 | 95,000 | 297,550 | 110,558 |
| Total cost items affected | $1,067,641 | $372,000 | $391,810 | $222,000 |

tunnel and would require the same electrical equipment. The estimated cost of the complete electrification at that time was $6,463,750 or $80,800, per route mile. Of this amount, $3,250,000 or 50.28 per cent, was for electric locomotives.

The savings from electrical operation estimated for items affected were $639,703. While a considerable portion of the savings shown in the above comparison favorable to electrical operation is due to the new tunnel which shortened the route and decreased the lift, this improvement would not have been practical without the electrical operation of the tunnel. The decision to build the tunnel was reached only after a careful report had been prepared which indicated that interest on the capital charge would easily be covered by the saving in like charges for new snow shed construction and in maintenance charges for same in the future, thus putting the investment for the new tunnel on a self-supporting basis.

The saving in operating expense shown is equal to 12.63 per cent on the gross cost of the electrification which, together with the shortened time and other improvements in the service, makes the electrification a favorable investment with a normal volume of traffic. The electrical equipment is easily capable of handling an increase of 50 per cent in the freight traffic and with such an increase, the saving in operating expenses would be in about the same proportion, making the return on the gross investment for electrification approximately 18 per cent.

TABLE II—COST OF ELECTRIFICATION WENATCHEE TO SKYKOMISH AFTER DEDUCTION OF $174,603.73 CREDIT FOR THE 14 MILES ABANDONED BETWEEN SCENIC AND CASCADE TUNNEL

Route miles 73
Track miles 91

| | Amount | Per route mile | Per cent of total<br>Less locomotives | Including locomotives |
|---|---|---|---|---|
| Substations, etc | $1,062,611 | $14,556 | 33.63 | 16.21 |
| Transmission system | 531,967 | 7,287 | 16.70 | 8.12 |
| Power distribution | 368,040 | 5,042 | 11.56 | 5.62 |
| Poles and fixtures | 567,265 | 7,771 | 17.81 | 8.66 |
| Telephone and telegraph changes | 157,440 | 2,157 | 4.94 | 2.40 |
| Signals and interlocks | 155,970 | 2,136 | 4.90 | 2.38 |
| Shops, machinery, tools | 138,357 | 1,895 | 4.34 | 2.11 |
| Engineering | 203,512 | 2,788 | 6.39 | 3.10 |
| Total less locomotives | $3,185,162 | $43,632 | 100.00 | 48.60 |
| Locomotives | $3,368,338 | $46,141 | | 51.40 |
| Total | $6,553,500 | $89,773 | | 100.00 |

The capacity of this portion of the line which, with a congestion of traffic, would, with steam operation, undoubtedly become the bottle neck of the system, has been increased 100 per cent as is indicated by the records. These show that whereas with steam operation in 1920, three steam locomotives averaged approximately six hours to take a 2,250-ton train the 24.3 miles from Skykomish to the old Summit, in 1929, two electric locomotives, averaged about 1½ hours to take a 5,000-ton train the 21.2 miles from Skykomish to the new summit, an increase in schedule speed of from four miles to 14 miles per hour more than double the tons in one-fourth the time on the most difficult grade.

In ton miles per train hour, this is 70,666 for the electric as against 9,112 for steam, a ratio of 7.7 to 1 in favor of electrical operation.

## Discussion

**W. F. Coors:** That part of the paper which gives the details of one of the unexpected electrical troubles encountered in the operation of these locomotives, is of particular appeal from a practical viewpoint. Electric locomotives, technically speaking, are very similar to substations on wheels for the conversion of electrical to mechanical energy. They have transformers or resistors, rotating parts, protective electrical equipment, controlled switching mechanism and some other features which bear similar functionary relation to the apparatus found in any substation used purely for the conversion of electrical energy. However, in addition to having the final output taking the form of mechanical energy, the electric locomotive in heavy trunk line service is exposed in operation to outdoor weather and climatic conditions with changes, dust and dirt, vibrations and road shocks, more infrequent cleanings and inspections; which conditions are not ordinarily met with in stationary work. The Great Northern locomotives with their motor-generator conversion of alternating to direct current for the traction motors, carry out the substation simile to a further degree.

The expected operation of electrical equipment in locomotives or substations is, of course, usually subject to prediction from preliminary tests with mathematical certainty. But on all large projects of this kind there are always, seemingly, certain local conditions which enter in to cause failures when operation is started; and these may have their seat in some one particular feature of design, small of itself apparently, but leading into complications. To solve such difficulties the past experience of the engineer renders itself to an advantage.

On the Milwaukee Road electrification there were several troubles encountered on electrical equipment due to unexpected moisture conditions affecting insulation. One of these was where the depression in the top of the traction motor frame housings for recessing the field pole cap-screw heads, filled with snow in some kinds of weather. The snow would melt later when the traction motors warmed up at work and the resulting water ran through the bolt holes into the traction motor cases. This usually resulted in field coil insulation failures. The application of battery sealing compound filling these recesses, obviated this difficulty.

Another kind of failure was possible because at first the electric locomotives were run into a steam engine house for repair. Coming in from below-zero weather outside, the metal parts would have a thick, white frost congeal on them from the warm, moist air inside the house. Then later, if the locomotive was held inside, this frost would melt slowly, the water dripping from armatures, field coils, and switches for some time during the melting process. If allowed to set for an appreciable period afterward, the insulation resistance of certain parts of the locomotive decreased to the point where failure was probable on the 3,000-d-c trolley current. Other parts where the water drained off freely gave less indication of this possibility. It was feasible to put such a locomotive in service after the frost had first congealed on the parts, before it started melting, in which case the brushes on the commutators sometimes scraped off frost 1/16 in. deep. A few flashovers were caused by this but operation was possible. While in operation, that part of the frost which melted on windings heated by carrying current, was found not to cause serious difficulty because to the heat working outwardly, the motor or such apparatus in service would have also a heavy draft of ventilating air through it, preventing the accumulation of moisture pockets resulting in the saturation of any insulating material.

Another difficulty came from snow being blown into the traction motor housings from the ventilating blower system on a certain type of the locomotives. The intakes of these blowers, while not entirely exposed, were under the cab structure on the trucks; and in weather where light, dry snow was falling, it would be sucked into the ventilating system and deposited on the traction motor armatures. This, in itself, might not have been disastrous but due to the internal ventilating ducts in the armature core structure, this snow would be trapped and melted in pockets with resultant insulation deterioration. These failures usually showed up some time later if the locomotive had been held under conditions for this trapped moisture to melt. Correction of such failures came from changing the ventilation system to what was similarly done later on the Great Northern Railway.

The experience gained from these and other electrifications indicates that certain refinements usually prove necessary after operation has started to take care of unprecedented local conditions. These are determinable mainly from experience in the manner that the automobile has been made so universally adaptable. Electric locomotive designers perhaps can find much of adaptability from the automobile designers; and can neglect much of former steam locomotive practise when it comes to things of purely legendary value. It is prospective that as more electric locomotives are built for more and more electrification work these accidental features of design failure will be worked out to complete elimination.

**R. T. Strong:** In considering any railway electrification, a careful distinction must be made between the terms "locomotive unit" and "locomotive." A locomotive may consist of one, two, three, or perhaps even more locomotive units.

It is assumed that the reader is familiar with the "standard system" of electric locomotive classification here used, in which numerals indicate non-driving axles, and letters indicate driving axles.

It was originally intended by the railway to have two types of locomotives, namely the two unit locomotive originally purchased, type 1 – D – 1 + 1 – D – 1, for freight service, and the single unit locomotive, type 1 – C + C – 1, for passenger service. However, it was soon found in operation that limiting the use of a particular class of locomotive to certain particular service, resulted in unnecessary expense through lost crew time, and dead mileage.

The most economical operation was obtained by using locomotives interchangeably in all types of service. Five different make-ups of locomotives are now in use, as shown by the following tabulation, operation in each case being in multiple, thus requiring only a single crew per locomotive. The flexibility of motive power thus obtained is clearly shown by the following table.

| No. of units per locomotive | Locomotive classification | Loco. weight (tons) | Tractive effort continuous (pounds) |
|---|---|---|---|
| 1 | 1 – D – 1 | 184 | 44,250 |
| 1 | 1 – C + C – 1 | 269.5 | 60,500 |
| 2 | 1 – D – 1 + 1 – D – 1 | 369 | 88,500 |
| 2 | 1 – C + C – 1 + 1 – C + C – 1 | 539 | 121,000 |
| 3 | 1 – D – 1 + 1 – D – 1 + 1 – D – 1 | 552 | 132,750 |

There is some slight discrepancy between the weights given above, and those previously published. The above weights are those of the latest units delivered.

From the above discussion it will be seen that the selection of unit sizes so as to obtain the greatest flexibility combined with the maximum standardization, is of the greatest importance in a new railway electrification. The Pennsylvania Railroad, in its electrification now in progress, has probably gone further than any other railway in this regard.

The flexibility of the single-phase equipment, is well illustrated by the conversion of two 50-ton locomotives and one passenger car from the old Inland Empire System at Spokane, for operation on the Great Northern main line electrification. The only change necessary was the substitution of transformers having an 11,000-volt high tension winding, in addition to the 6,600-volt winding used on the Inland Empire System. For nearly a year, during which time the condensation difficulties described by Mr. Cox occurred, one of these locomotives which was then 23 years old, regularly made two trips per day with a local passenger train over the main line electrification.

The history of most railway electrifications is that the train weights originally specified by the railway have rarely been adhered to. As the railway operating officials observe the ease and economy with which the electrification handles large trains, they keep continually increasing the train sizes. This is well illustrated by the statement in the paper under discussion, that the original three-phase electrification in the old Cascade Tunnel was designed to pull a maximum of 1,600 tons, but actually trains of 2,200 tons were pulled before the tunnel was abandoned. Likewise, the new electrification was first designed for a maximum of 3,500-ton trains, but 5,000-ton trains are now being handled. It was at first thought that the Tumwater Power Plant of 4,000-kw capacity, supplemented by only a small amount of additional power, would be sufficient for the electrification. Actually, the present power supply at Skykomish, Tumwater, and Wenatchee totals 19,000 kw.

The point of this discussion is that the electrical engineer laying out a new railway electrification must keep in mind this tendency, and leave an ample margin in the design for increases in train weight.

Also this tendency introduces a dangerous factor, inasmuch as steam railway operating men are accustomed to loading their steam motive power to its limit. Steam equipment will protect itself by refusing the load before it damages itself. Electric motive power does not thus protect itself, and overload does not show up immediately, but appears at some later time in the form of excessive maintenance cost. Therefore the electrical engineer must carefully watch the operating temperatures of his equipment in a new electrification, to prevent overloading due to this tendency of the operating men to push the equipment to its limit.

In connection with the condensation difficulties described in this paper, there were two conditions contributing to the high temperatures in the tunnel which are not mentioned; first, the presence of warm springs in the tunnel; and second, the heat thrown off by the chemical action of the setting of the newly poured concrete. Colonel F. Mears, Assistant Chief Engineer of the Great Northern Railway, has some very interesting figures on this second condition, showing that newly poured concrete gives off appreciable amounts of heat for a long period of time.

The effect of these two conditions is shown by the fact that one year after the opening of the tunnel, under practically identical weather conditions, the maximum temperature inside the tunnel was only 56 deg F, a drop of 9 degrees from the figure shown by Mr. Cox.

The condensation difficulties were aggravated by the fact that the tunnel air was completely saturated with moisture from the quantities of warm water draining out alongside the track. The eastern end of the tunnel was filled with steam for nearly one mile, and a plume of steam constantly rose from the east portal. The difficulties with the locomotives were entirely due to condensation within the cabs, and not to snow or water drawn in from the outside.

In the case of the 1 – D – 1 locomotive, dampers were installed in the air ducts, with two settings, "summer operation" and "winter operation." In the position marked "summer operation" the air is drawn from the outside, and discharged to the outside of the cab. In the position "winter operation," a large proportion of the air is recirculated within the cabs. It is only necessary to change the position of these dampers twice each year.

These conditions deserve being discussed rather fully, in order that they may be foreseen and provided for by the electrical engineer in future similar projects. It is rather an anomaly, that after designing the ventilation of the cabs with a view primarily to keeping the electrical equipment cool, that it was necessary to change the air circulation so as to keep the equipment warm.

No mention was made in the paper of the catenary system. The Great Northern Railway used the simple inclined catenary similar to that described in Mr. G. I. Wright's paper on the Reading Electrification, as distinguished from the chord catenary used by the Chicago, Milwaukee, St. Paul & Pacific Railway Company. With the inclined catenary the messenger cable is offset from the center of the track on curves, sufficiently so that it acts also as a backbone, thus eliminating most of the pull-offs. The correct position of the trolley wire is obtained by varying the length and angles of the hangers. In the chord catenary the messenger cable is held in the center of the track directly over the trolley wire, by pull-offs and a separate backbone.

A very complete and comprehensive report on the Great Northern electrification will be found in Publication No. 079, "Report of the Committee on Electrification of Steam Railroads," of the National Electric Light Association, September 1930.

**G. H. Walker:** In connection with the paper it may be of interest to outline briefly the electrical system of this electrification. Power is purchased at three-phase 60 cycles at Skykomish and Wenatchee and at 25 cycles single-phase at the Tumwater hydroelectric plant on the Wenatchee river, about twenty-five miles west of Wenatchee, from the Puget Sound Power and Light Company. Frequency changers at Skykomish and Wenatchee convert the three-phase 60-cycle power to single-phase 25-cycle and the three points of power delivery are connected with a double circuit single-phase 44-kv transmission line. The contact system is 11,500 volts single-phase 25 cycles. It is simple catenary construction inclined on curves supported from steel bracket arms on wood poles. This contact system is fed at Skykomish and Wenatchee from the frequency changers stations and from the 44-kv transmission circuits at five intermediate points through stepdown transformers located adjacent to the track.

Power is purchased under a so-called two-part contract, providing for a maximum demand charge plus an energy charge. The demand charge has a primary and secondary rate. The first 5,000 kw are charged for at the primary rate and the next 8,000 kw at the secondary rate. Demand in excess of 13,000 kw is charged for at the primary rate. The maximum demand is determined by the average of the three highest five-minute periods occurring, simultaneously at the three points of delivery, each month.

Because of the increase in demand charge when 13,000-kw demand is exceeded, the railway company finds it advisable to limit the demand to that amount. The method by which the demand is limited may be of interest. Each locomotive unit is equipped with an indicating ammeter on a meter panel visible to the engineman, which is connected in the circuit to the synchronous motor of the motor-generator set. Tests have been conducted to determine the demand for various readings on this ammeter for each type of locomotive unit. The results of these tests have been tabulated in a convenient form and furnished to the train dispatchers. It is the duty then of the train dispatcher in dispatching trains to assign a load limit to each locomotive unit on the line for any given period of time. This he does by orders to the engineman not to exceed so many amperes between certain points or certain times. This system of load limitation has certain serious disadvantages, in that it does not permit a train ascending a grade to take advantage of the reduction in power demand due to another train, descending a grade under regeneration or standing at a station for a meet. However, in the case of the Great Northern Railway, with its relatively short electrification and few number of trains, this method of power limitation has been used without undue handicap to schedules and resulting in a considerable saving in power costs.

Three of the 1 – D – 1 + 1 – D – 1 or Westinghouse locomotives were purchased with standard couplers between the two units. Late in 1929 equipment was purchased and installed in these units to permit operation of one, two or three units as one locomotive. Each unit of this type has the capacity to handle 750 tons on the 2.2 per cent grade or a capacity of 2,250 tons for the three-unit locomotive. This three-unit locomotive has now become practically standard for road freight service. Eastbound out of Skykomish this three-unit road engine with a two-unit helper engine to Merritt will handle 3,750 tons which is the average train. Trains of 4,750 tons have been handled east out of Skykomish with the three-unit 1 – D – 1 road engine, a two-unit 1 – D – 1 and a single unit 1 – C + C – 1 helper engines. The 5,300-ton trains, which are the heaviest handled so far, have used the three-unit road engine and two 1 – D – 1 + 1 – D – 1 helper engines. Westbound this three-unit road engine will handle 3,500 tons from Wenatchee to Merritt without a helper. Schedules are arranged so that eastbound freight trains arrive at Merritt (the foot of the 2.2 per cent grade on the east slope) before the westbound train. Thus the helpers which were cut out of the eastbound train at Merritt are available to help westbound trains up the grade to Berne and continue in the train down to Skykomish.

The 1 – C + C – 1 or General Electric locomotive units also are grouped one, two or three units as a single locomotive for road freight service. A two-unit locomotive of this type will handle 2,000 tons on the 2.2 per cent grade and 3,000 tons on the 1.6 per cent grade westbound. A three-unit locomotive will handle 3,000 tons on the 2.2 per cent grade and 4,500 tons on the 1.6 per cent grade. Eastbound out of Skykomish 4,500-ton trains have been handled by this type three-unit road engine and a 1 – D – 1 + 1 – D – 1 helper engine. Westbound the three-unit 1 – C + C – 1 road engine has handled 4,500 tons from Appleyard to Merritt without a helper. The three 1 – D – 1 unit engine has a continuous output rating of 5,400 hp with a tractive effort of 132,750 lb. The three 1 – C + C – 1 unit engine has a continuous output rating of 9,000 hp and a tractive effort of 181,500 lb.

Table I gives some power consumption and traffic data for the year 1931.

TABLE I—POWER CONSUMPTION AND TRAFFIC DATA GREAT NORTHERN RAILWAY CASCADE ELECTRIFICATION
Year 1931

| | |
|---|---|
| Kwhr purchased | 24,335,844 |
| Kwhr purchased—traction | 23,904,888 |
| Kwhr signals and miscellaneous | 430,904 |
| Kwhr traction—measured on locomotives | 16,528,090 |
| Kwhr hostling and switching—measured at locomotives | 1,797,714 |
| Distribution system efficiency[1] | 69.14% |
| Maximum demand (12,350 monthly average) | 13,107 kw |
| Annual load factor (22.50% avg max. demand) | 21.20% |
| Cost per kwhr purchased power | $0.009676 |
| Kgtm[2] freight and passenger traffic | 331,907 |
| Kwhr per kgtm[2] freight and passenger traffic purchased | 72.02 |
| Kwhr measured at locomotives freight and passenger traffic | 14,730,376 |
| Kwhr per kgtm[2] freight and passenger traffic—measured at locomotives | 44.38 |
| Kgtm[2] freight traffic | 229,857 |
| Average tons per train freight (3,757 east, 2,994 west) | 3,375 |
| Kwhr measured at locomotives freight traffic | 9,323,020 |
| Kwhr per ktgm freight—measured at locomotives | 40.56 |
| Kgtm[2] passenger traffic | 102,050 |
| Average tons per train passenger (9 cars) | 637 |
| Car miles passenger traffic | 1,457,896 |
| Kwhr measured at locomotives passenger traffic | 5,407,356 |
| Kwhr per kgtm[2] passenger—measured at locomotives | 52.99 |
| Kwhr per passenger car mile—measured at locomotives | 3.71 |
| Locomotive overall efficiency[3] ..... Motoring | 65% |
| Regenerating | 60% |

[1] Distribution system is used to transfer surplus power from hydroelectric power station on Railway Co's. system to Power Co's. system. When this function is considered and proportionate losses charged to it the distribution system efficiency becomes 85 per cent.

[2] Thousands of gross ton miles.

[3] Locomotive efficiencies were determined by comparing the measured input to the locomotive with a theoretical output calculated for an average tonnage train run over the profile in each direction.

# Theory of the Three-Wire D-C. Generator with Two-Phase Static Balancer

## With Special Reference to Magnetic Phenomena in the Balance Core

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***Synopsis.**—When a three-wire d-c. generator with a two-phase static balancer operates with an unbalanced load it is possible that cumulative saturation effects may exist in the balancer core whose magnitude is out of all proportion to the small magnetic unbalance which usually results from the design of the balancer phases. By obtaining an expression for the e.m.f. induced in the balancer winding by the alternating flux the conditions under which these phenomena may be present are studied. It is shown that they are affected by any difference in the resistance of the phases, and that in general their magnitudes vary inversely as the sum of the resistances of the armature winding and the balancer.*

*These conclusions are confirmed by test results and oscillograms taken on an actual machine which show that the maximum flux density in the balancer core may rise to as much as twice the value for which it was designed. The large peaks which occur in the magnetizing current affect the heating of the balancer and also, to a less extent, that of the generator. They also cause considerable pulsations in the terminal voltages of the system.*

### INTRODUCTION

The exact theory of the three-wire generator with static balancer is not simple, as has been shown by Sengel, Hawkins, and others.† It can be shown that the difference of the voltages on the two sides of the system, when the load is unbalanced, pulsates slightly with double frequency, and Hawkins shows that the out-of-balance current, when entering the balancer coils, does not divide into two equal and unchanging halves (we shall confine our discussion to the two-phase case) but into two portions which pulsate with fundamental frequency but whose mean values are equal.

It is often assumed that the two halves of the balancer winding have exactly equal magnetic effects on the iron core, so that the out-of-balance currents have no direct magnetizing effect. In practise, however, it is extremely difficult, if not impossible, to construct the coils in such a way that their magnetic effects are completely balanced, though any unbalance is usually very small.

It is well known that if an alternating flux is superposed on a direct flux in an iron core the magnetizing current will have dissimilar half-waves, introducing even harmonics (including a constant term) into its analysis. In tests made on a two-phase balancer, in which every effort had been made in its design to balance the two halves of the winding, it was found that even-harmonic peaks occurred in the magnetizing current with an unbalanced load of such a magnitude that they could not be accounted for in a simple manner by the small magnetic unbalance of the phases. Furthermore, it was found that the presence of such peaks was affected by any inequality in the resistances of the two phases of the balancer; with certain conditions of balancer resistance and unbalanced load the peaks were not present at all, and in such cases further increase of unbalanced load resulted in a complete reversal of the phenomena.

The normal magnetizing current of the balancer tested was about 0.25 ampere, while the magnitude of the peaks varied up to over twice the value of the unbalanced direct current, the ratio of peak to unbalanced current decreasing as the latter was increased. Oscillogram No. 7 shows a peak of 58 amperes with an unbalanced current of 63 amperes.

An attempt is made in this paper to give the theory of the two-phase balancer in such a way as to include the explanation of these phenomena.

### THEORY OF THE TWO-PHASE BALANCER

*Mathematical Analysis.* The connections of a two-pole three-wire generator with static balancer are shown in Fig. 1. The balancer is shown external to the machine, being connected to the two diametrical tapping points $C$ and $D$ on the armature winding by means of two slip-rings.

*List of Symbols*

$I_1$ = the load current on the positive side of the system.
$I_2$ = the load current on the negative side.
$(I_1 - I_2)$ = the unbalanced current in the neutral wire.
$R_1$ = the equivalent resistance of the load on the positive side, including the resistance of the leads exterior to the machine and the balancer.
$R_2$ = the equivalent resistance of the load on the negative side.
$R_a$ = armature resistance, measured between brushes.
$R_3$ = resistance of balancer winding and leads between the points $E$ and $C$.

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†See Bibliography.

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$R_4$ = resistance of balancer and leads between $E$ and $D$.

$R_b$ = total resistance of balancer winding and leads, $= R_3 + R_4$.

$L$ = leakage inductance of each parallel path of the armature winding.

$L_1$ = leakage inductance of portion $EC$ of balancer winding.

$L_2$ = leakage inductance of portion $ED$ of balancer winding.

$i_1$ = instantaneous current in balancer winding from $D$ to $C$.

$i_2$ = instantaneous current in portion $CB$ of armature winding.

$e_1$ = instantaneous e.m.f. induced in portions $CB$ and $AD$ of armature winding.

$e_2$ = instantaneous e.m.f. induced in portions $AC$ and $DB$ of armature.

$V_1$ = potential difference across positive lead and neutral.

$V_2$ = potential difference across negative lead and neutral.

$V$ = potential difference across outers of system $= V_1 + V_2$.

$\omega$ = angular velocity of armature.

$t$ = time, starting from the instant when $C$ is at $A$, and again from the instant when $C$ is at $B$.

$q$ = angle $AOC$ divided by $\pi = \dfrac{\omega t}{\pi}$,

$e_3$ = instantaneous e.m.f. induced in each half of balancer winding by the mutual flux. (Each phase is assumed to have the same number of turns.)

The leakage inductances $L$, $L_1$ and $L_2$ are assumed constant, $L$ is assumed to be evenly distributed over the armature.* For the portions $AC$ and $DB$ of the armature we therefore have:

$$\begin{aligned} \text{resistance} &= 2R_a q \\ \text{inductance} &= Lq \end{aligned}$$

and for the sections $CB$ and $AD$:

$$\begin{aligned} &\text{resistance } 2R_a(1-q) \\ &\text{inductance} = L\,(1-q) \end{aligned}$$

It is clear that in a drum armature the e.m.fs. generated by the field flux in the sections $AC$ and $DB$ must be equal, as are also those generated in $CB$ and $AD$, no matter how the flux may be distorted by armature reaction. Hence the use of the symbols $e_1$ and $e_2$ as above.

The load currents $I_1$ and $I_2$ are assumed to be constant for a steady condition of load. This is not strictly true, but very little error is introduced by neglecting their inductive effects when compared with those of $i_1$ and $i_2$.

The instantaneous currents in the various parts of the circuit will then be as shown in Fig. 1. It is important to notice that the current $i_1$ takes care of any inequality in division of the unbalanced current $(I_1 - I_2)$ in the balancer phases. The total flux set up in the balancer core will be due to the m.m.f. of $i_1$ plus the unbalanced m.m.f. of the currents $\dfrac{(I_1 - I_2)}{2}$ flowing in opposite directions in the two phases.

Since the e.m.fs. generated at any instant in each parallel path of the armature are equal, it follows that the voltage drop in each path, $ACB$ and $ADB$, due to the flow of the armature currents must be the same.

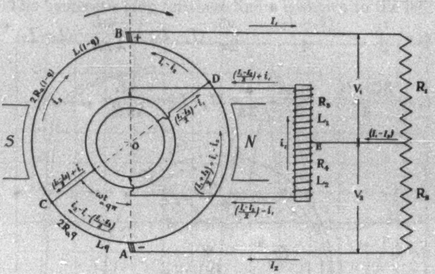
B
+
$L(1-q)$
$2R_a(1-q)$
$i_2$
$I_1 - i_2$
D
$\left(\frac{I_1-I_2}{2}\right)+i_1$
$\left(\frac{I_1-I_2}{2}\right)-i_1$
$I_1$
$V_1$
$R_1$
$R_3$
$L_1$
S
O
N
$i_1$
E
$(I_1-I_2)$
$R_4$
$L_2$
$V_2$
$R_2$
$\left(\frac{I_1+I_2}{2}\right)+i_1-i_2$
$\left(\frac{I_1-I_2}{2}\right)+i_1$
C
$\omega t = q\pi$
$i_2-i_1-\left(\frac{I_1-I_2}{2}\right)$
$2R_a q$
$Lq$
A
−
$\left(\frac{I_1-I_2}{2}\right)-i_1$
$I_2$

FIG. 1—CONNECTION DIAGRAM OF THREE-WIRE GENERATOR WITH TWO-PHASE STATIC BALANCER

The voltage drop in $ACB$ reduces to:

$$2R_a\left[i_2 - q\left(\frac{I_1 - I_2}{2} + i_1\right)\right] + L\left(\frac{di_2}{dt} - q\,\frac{di_1}{dt}\right) \quad (1)$$

and the drop in $ADB$ reduces to:

$$2R_a\left[\frac{I_1 + I_2}{2} + i_1\,(1-q) - i_2 + q\left(\frac{I_1 - I_2}{2}\right)\right]$$

$$+ L\left[\frac{di_1}{dt}\,(1-q) - \frac{di_2}{dt}\right] \quad (2)$$

The expressions (1) and (2) must be equal, hence we get:

$$2R_a\left[\frac{(I_1 + I_2)}{2} + q\,(I_1 - I_2) + (i_1 - 2i_2)\right]$$

$$+ L\left(\frac{di_1}{dt} - 2\,\frac{di_2}{dt}\right) = 0 \quad (3)$$

---

*Actually the leakage inductance under the poles will not be the same as that between the poles. If, however, we take this into account by putting the inductances of the sections $AC$ and $DB$ each equal to $L_3$, and those of $CB$ and $AD$ equal to $L_4$, the fundamental equations (**12a**) and (**12b**) are unaltered.

Solving this differential equation in $(i_1 - 2i_2)$ we obtain a steady condition given by:

$$2i_2 = i_1 + \frac{(I_1 + I_2)}{2} + \frac{\omega t}{\pi}(I_1 - I_2) - \frac{\omega L}{2\pi R_a}(I_1 - I_2) \tag{4}$$

Substituting for $i_2$ in the circuits of Fig. 1 gives the equivalent network of Fig. 2. The arrows show the positive directions of the currents and the induced e.m.fs.

The armature currents are:

$$c_1 = \frac{i_1}{2} + \frac{(I_1 + I_2)}{4} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_2 = \frac{3I_1 - I_2}{4} - \frac{i_1}{2} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_3 = \frac{i_1}{2} + \frac{(I_1 + I_2)}{4} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_4 = \frac{3I_2 - I_1}{4} - \frac{i_1}{2} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

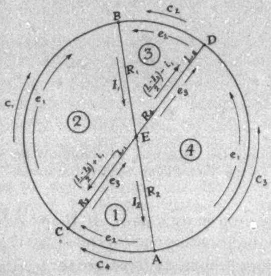

FIG. 2—EQUIVALENT CIRCUIT, AND DISTRIBUTION OF CURRENTS

(For actual values of $c_1$, $c_2$, $c_3$, and $c_4$ see text)

Applying Kirchhoff's second law to the closed circuits (1), (2), (3), and (4) of Fig. 2 we obtain the following equations:

$$2R_a \frac{\omega t}{\pi}\left[\frac{3I_2 - I_1}{4} - \frac{i_1}{2} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] - \left[\frac{(I_1 - I_2)}{2} + i_1\right]R_3 + I_2R_2 + L\frac{\omega t}{\pi}\left[-\frac{1}{2}\cdot\frac{di_1}{dt} + \frac{\omega}{2\pi}(I_1 - I_2)\right] - L_1\frac{di_1}{dt} = e_2 + e_3 \tag{5}$$

$$2R_a\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{i_1}{2} + \frac{(I_1 + I_2)}{4} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_1R_1 + \left[\frac{(I_1 - I_2)}{2} + i_1\right]R_3 + L\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{1}{2}\cdot\frac{di_1}{dt} + \frac{\omega}{2\pi}(I_1 - I_2)\right] + L_1\frac{di_1}{dt} = e_1 - e_3 \tag{6}$$

$$2R_a\frac{\omega t}{\pi}\left[\frac{3I_1 - I_2}{4} - \frac{i_1}{2} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_1R_1 + \left[\frac{(I_1 - I_2)}{2} - i_1\right]R_4 + L\frac{\omega t}{\pi}\left[-\frac{1}{2}\cdot\frac{di_1}{dt} - \frac{\omega}{2\pi}(I_1 - I_2)\right] - L_2\frac{di_1}{dt} = e_2 + e_3 \tag{7}$$

$$2R_a\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{i_1}{2} + \frac{I_1 + I_2}{4} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_2R_2 - \left[\frac{(I_1 - I_2)}{2} - i_1\right]R_4 + L\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{1}{2}\cdot\frac{di_1}{dt} - \frac{\omega}{2\pi}(I_1 - I_2)\right] + L_2\frac{di_1}{dt} = e_1 - e_3 \tag{8}$$

These four equations also express the fact that the voltage drops in the armature paths $ACB$ and $ADB$ are equal, which has already been made use of; one of them, therefore, is redundant.

Equating the left-hand sides of equations (5) and (7) gives:

$$(V_2 - V_1) = (I_2R_2 - I_1R_1) = (I_1 - I_2)\left[\frac{R_b}{2} + 2R_a\left\{\frac{\omega t}{\pi} - \left(\frac{\omega t}{\pi}\right)^2\right\}\right] + (L_1 - L_2)\frac{di_1}{dt} + i_1(R_3 - R_4) \tag{9}$$

If $L_1 = L_2$ and $R_3 = R_4$ equation (9) reduces to the well-known result for the voltage unbalance of a two-phase balancer:

$$\text{Mean value of } (V_2 - V_1) = (I_1 - I_2)\left(\frac{R_b}{2} + \frac{R_a}{3}\right) \tag{10}$$

It should be noted that equation (**9**) is true for both halves of the cycle. In the second-half of the cycle, since $i_1$ is defined as the current in the balancer from $D$ to $C$, the circuits of Fig. 2 hold good if the sign of $i_1$ is reversed and if the time $t$ is measured from the instant when $C$ is at the brush $B$. Also, $R_3$ and $R_4$ must be interchanged, as must $L_1$ and $L_2$, while for continuity of armature e.m.fs. $e_1$ and $e_2$ must replace each other and $e_3$, whose direction is from $C$ to $D$, will reverse its direction relative to the brushes $A$ and $B$. It follows from this that the equation (**9**) is true for both halves of the cycle provided the time $t$ starts from zero whenever the point $C$ passes a brush.

Again, by subtracting equation (**5**) from (**6**), we obtain:

$$\frac{di_1}{dt}\left(\frac{L}{2}+2L_1\right)+i_1\,(R_a+2R_3)$$

$$+\,R_a\frac{\omega t}{\pi}\,(I_1-3I_2)-2R_a\left(\frac{\omega t}{\pi}\right)^2(I_1-I_2)$$

$$+\,(I_1-I_2)\,R_3+(I_1R_1-I_2R_2)$$

$$+\,\frac{(I_1+I_2)}{2}\cdot R_a=e_1-e_2-2e_3 \qquad \textbf{(11)}$$

Substituting for $(I_1R_1-I_2R_2)$ from equation (**9**) we get:

$$2e_3=(e_1-e_2)-\frac{di_1}{dt}\left(\frac{L}{2}+L_1+L_2\right)-i_1(R_a+R_b)$$

$$+R_a(I_1+I_2)\left(\frac{\omega t}{\pi}-\frac{1}{2}\right)+(R_4-R_3)\,\frac{(I_1-I_2)}{2} \qquad \textbf{(12a)}$$

and for the second-half of the cycle ($t$ starting again from zero):

$$2e_3=(e_1-e_2)-\frac{di_1}{dt}\left(\frac{L}{2}+L_1+L_2\right)-i_1(R_a+R_b)$$

$$-R_a(I_1+I_2)\left(\frac{\omega t}{\pi}-\frac{1}{2}\right)+(R_4-R_3)\left(\frac{I_1-I_2}{2}\right) \qquad \textbf{(12b)}$$

It is not possible to determine $i_1$ mathematically, due to the phenomena of saturation and hysteresis in the balancer core; it is in the correct interpretation of the equations (**12a**) and (**12b**), which give the e.m.f. induced in the balancer by the mutual flux, that we shall find the factors which govern the variation of $i_1$.

The fundamental principle which we shall use is that, under steady conditions, the expressions for $2e_3$ as given by the equations (**12**) cannot contain a constant term when all the varying terms are expressed as Fourier series. Since the e.m.f. $2e_3$ is caused solely by a changing flux linking the balancer turns, it follows that every harmonic present in this e.m.f. must be caused by a like harmonic in the mutual flux, and a constant term in the e.m.f. would require for its generation a component of flux which increases continuously at a uniform rate, which is impossible. Hence there cannot be a constant term in the harmonic analysis of the expression for $2e_3$.*

*Effect of Even Harmonics in an Alternating Flux On the Magnetizing Current.* So long as the wave-form of an alternating magnetic flux contains only odd harmonics it follows that the magnetizing current or m.m.f. wave which causes the flux can only contain odd harmonics; as soon, however, as even harmonics (which may include a constant term) appear in the flux wave, greatly magnified even harmonics will be introduced in the magnetizing current wave if the flux density approaches saturation values.

In Fig. 3 is shown the result of a constant term in the flux wave. The flux, when expressed in terms of flux density, has the equation:

$$\Phi = 25 + 80 \sin \omega t$$

Consequently the positive peak of the flux wave has a value of 105 while the negative peak only reaches 55. The hysteresis loop for these limits is shown to the left of the figure, and due to saturation it is seen that the positive loop of the flux wave will require a very much larger m.m.f. or magnetizing current than the negative loop. The actual magnetizing current wave is shown at $i$ in the figure, and it is seen to have very large peaks once a cycle. (The actual scale of current is purely relative.)

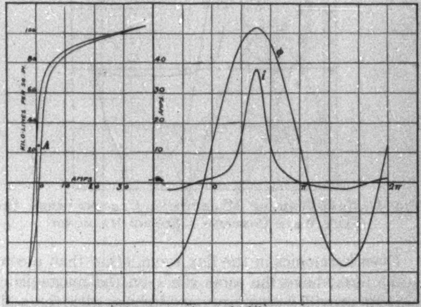

FIG. 3—WAVE-FORM OF MAGNETIZING CURRENT WHEN THE FLUX WAVE CONTAINS A CONSTANT TERM

The harmonic analysis of the current $i$ in Fig. 3, as far as the eighth harmonic, is approximately:

$$i=5.7+1.0\cos\theta+11.8\sin\theta-8.4\cos 2\theta+0.9\sin 2\theta$$

$$-\,5.4\sin 3\theta+3.3\cos 4\theta+2.0\sin 5\theta-1.0\cos 6\theta$$

$$-\,0.54\sin 7\theta+0.4\cos 8\theta \qquad \textbf{(13)}$$

where $\theta = \omega t$

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*It has been necessary, in developing the equations (**12a**) and (**12b**), to distinguish between the two halves of the cycle and to introduce a discontinuity in the time $t$. It is easily seen, however, that the equations (**12a**) and (**12b**) can be combined into one expression for $2e_3$ in which all the variables are expressed as Fourier series and in which the time $t$ increases uniformly with no discontinuity.

The wave thus contains a large constant term (5.7) and even harmonics, of which the most important is the second. If there were no core loss all the odd harmonics would be pure sine terms, and all the even harmonics would be pure cosine terms.

The magnetizing current wave when a sinusoidal flux (or a flux containing only odd harmonics) is superposed on a direct flux which is maintained by a separate m.m.f. is very nearly the same as that shown in Fig. 3, the only difference being that the origin of the hysteresis loop would be midway between the positive and negative maxima of flux density; *i. e.*, the origin would be at the point *A* in Fig. 3. The magnitude of the current peak would be only slightly less than that shown.

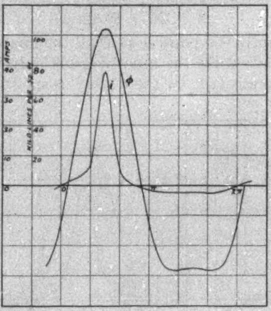

Fig. 4—Wave-Form of Magnetizing Current when the Flux Wave Contains a Second Harmonic

Even harmonics in the flux wave, other than a constant term, have the same effect on the magnetizing current provided they are out-of-phase with the odd-harmonic part of the wave. For example, a flux given by:

$$\Phi = 80 \sin \omega t - 25 \sin 2\omega t$$

has equal positive and negative maxima, and consequently no peaks would appear in the magnetizing current, but a flux given by:

$$\Phi = 80 \sin \omega t - 25 \cos 2\omega t$$

has the same positive maximum and nearly the same negative maximum as that shown in Fig. 3, so that the magnetizing current will have the same peak value as before, as is seen in Fig. 4. It will be noticed, however, that the peak is much narrower than in Fig. 3, so that the constant term is less. When analyzed as far as the ninth harmonic, the current *i* in Fig. 4 is given, approximately, by:

$$\begin{aligned} i_1 = {} & 3.02 + 0.86 \cos \theta + 9.16 \sin \theta - 6.8 \cos 2\theta + 0.8 \sin 2\theta \\ & - 4.9 \sin 3\theta + 3.85 \cos 4\theta + 3.1 \sin 5\theta - 2.3 \cos 6\theta \\ & - 1.62 \sin 3\theta + 1.15 \cos 8\theta + 0.76 \sin 9\theta \qquad \textbf{(14)} \end{aligned}$$

where $\theta = \omega t$

Comparing this expression with (**13**), we see that the harmonics up to and including the third are greater in (**13**) than in (**14**), but that those of a higher order are greater in (**14**).

It should be noticed that in both expressions the even harmonics (neglecting the sine terms, which are small) are alternatively positive and negative. It is easily seen that if a flux wave contains a positive fourth harmonic, a negative sixth, a positive eighth, etc., in cosine terms, then all these harmonics will add up to increase the positive maximum and decrease the negative maximum of the flux wave and so increase the value of the peak in the magnetizing current.

*Significance of the Equations* (**12a**) *and* (**12b**). Referring now to equations (**12a**) and (**12b**), which together give the instantaneous value of the e.m.f. induced in the balancer winding by the flux which is mutual to both phases at any instant during a complete revolution of the armature of the machine, we have already stated that the expression for this e.m.f., when each term is expressed in the form of a Fourier series, can contain no constant term under steady conditions. Let us now consider each term separately.

1. The term $(e_1 - e_2)$ gives the e.m.f. generated in the machine between the tapping points *C* and *D*. It is an alternating e.m.f., and if the total flux per pole is the same during each half of the revolution of the armature its wave-form will not contain a constant term or even harmonics. We shall see later, however, that $(e_1 - e_2)$ can contain a constant term due to armature reaction.

2. The differential coefficient $\dfrac{d i_1}{dt}$ cannot contain a constant term; since $i_1$ can always be expressed as a Fourier series of a constant term and sine and cosine terms, it follows that its differential coefficients cannot contain any constant term.

3. We have already seen that, under conditions of unequal positive and negative flux maxima, a magnetizing current may contain a constant term. The current $i_1$ is practically equal to the magnetizing current which sets up the flux which induces the e.m.f. $2e_3$, so that we must admit the possibility of a constant term in its analysis.

4. The term

$$R_a (I_1 + I_2) \left( \frac{\omega t}{\pi} - \frac{1}{2} \right)$$

varies over the complete cycle with a triangular wave-form of fundamental frequency, since its sign changes and *t* starts again from zero at the beginning of the second half-cycle. Its mean value is clearly zero, and its harmonic analysis consists of odd cosine terms only It therefore has no constant term.

5. The term

$$(R_4 - R_3) \frac{(I_1 - I_2)}{2}$$

is itself constant, and depends for its existence on an unbalance of resistance of the two phases of the balancer. It varies directly as the out-of-balance current. It is zero both when the load on the two sides of the system is balanced and also if the two phases have equal resistances.

In general, if any dissymetry in the flux variation introduces a constant term into the current $i_1$, then this constant term can only exist if the other terms of equation (**12**) have constant terms of such a sign and magnitude that the sum of all the constant terms in the expression for $2e_3$ vanishes.

*Effect of Slight Magnetic Unbalance of the Two Phases of the Balancer.* Now suppose that there is a slight magnetic unbalance of the two phases of the balancer in favor of the side *CE* (Figs. 1 and 2). That is to say, if equal currents are flowing in the two halves in opposite directions, there will be a small flux set up in the core in the direction of the m.m.f. of the side *CE*. It follows then, that if the positive side of the three-wire system is the more heavily loaded (as is shown in the diagrams) the components of current $\dfrac{(I_1 - I_2)}{2}$ in the two phases will set up a small flux in the direction *DC*.

Assuming, to start with, that the alternating flux in the balancer core only contains odd harmonics, it is clear that when this flux is in the direction *DC* the maximum value of the total flux will be greater than its maximum value in the direction *CD*, so that the magnetizing current wave will be distorted in the way shown in Fig. 3, the peaks occuring at the instant of maximum flux in the direction *DC*.

Now let the unbalanced m.m.f. of the two halves of the winding be equal to that produced by a steady current $I_0$, proportional to the out-of-balance current, flowing through the balancer from *D* to *C*, then clearly:

Total flux-producing current

$$= I_0 + i_1 = i_m \qquad (\mathbf{15})$$

and is of the form shown as $i$ in Fig. 3. It is important to notice that, no matter how small the unbalanced effect may be, the true magnetizing current given by (**15**), and hence $i_1$, will have a peak as shown, so long as the magnetization curve begins to bend over at the maximum value of flux density, though of course this peak may be very small.

Let us now study the effect of this slight peak in the magnetizing current on the mutual flux in the balancer core

Let

$$i_m = I_{m0} + I_{m1}(\sin \omega t + \theta_1) - I_{m2} \cos 2\omega t - I_{m3} \sin 3\omega t + I_{m4} \cos 4\omega t + \text{etc.} \qquad (\mathbf{16})$$

then it follows from (**15**) that the current $i_1$ contains the even harmonics $- I_{m2} \cos 2\omega t$, $+ I_{m4} \cos 4\omega t$, etc.

The induced voltage $2e_3$ (equations (**12a**) and (**12b**) will therefore contain the even harmonics:

$$- \left(\frac{L}{2} + L_1 + L_2\right) 2\omega I_{m2} \sin 2\omega t$$
$$+ (R_a + R_b) I_{m2} \cos 2\omega t$$
$$+ \left(\frac{L}{2} + L_1 + L_2\right) 4\omega I_{m4} \sin 4\omega t$$
$$- (R_a + R_b) I_{m4} \cos 4\omega t - \text{etc.}$$

These are equivalent to:

$$- I_{m2} \sqrt{\{\omega L + 2\omega (L_1 + L_2)\}^2 + (R_a + R_b)^2} \,.\, \sin \left(2\omega t - \tan^{-1} \frac{R_a + R_b}{\omega L + 2\omega (L_1 + L_2)}\right)$$
$$+ I_{m4} \sqrt{\{2\omega L + 4\omega (L_1 + L_2)\}^2 + (R_a + R_b)^2} \,.\, \sin \left(4\omega t - \tan^{-1} \frac{R_a + R_b}{2\omega L + 4\omega (L_1 + L_2)}\right) - \text{etc.}$$

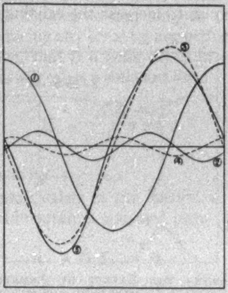

FIG. 5—SHOWING THE EFFECT ON THE FLUX WAVE OF EVEN HARMONICS INTRODUCED INTO THE INDUCED VOLTAGE WAVE BY A DISTORTED MAGNETIZING CURRENT

The curves show:

(1) That part of the induced e.m.f. $2e_3$ which consists entirely of odd harmonics. For simplicity it is shown as a sine curve

(2) The second harmonic component of $2e_3$

(3) The mutual flux which induces the e.m.f (1)

(4) The mutual flux which induces the e.m.f. (2)

(5) The total mutual flux, which has a greater maximum in the direction *DC* than in the direction *CD*

Each of the phase angles in the above expressions is small,* since the leakage reactance $\{\omega L + 2\omega (L_1 + L_2)\}$ is larger than the resistance $(R_a + R_b)$. Now each of the even harmonics in the induced voltage $2e_3$ requires a like harmonic in the mutual flux, leading it by 90 electrical degrees referred to its own frequency, and these even harmonics in the flux combine to increase the flux maximum in the direction *DC* and to decrease it in the direction *CD*. This is shown graphically in Fig. 5, in which the positive direction of all quantities

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*Even if $(R_a + R_b)$ is very large, the phase angles will be less than 90 degrees of the harmonic frequency, and the increase of one of the flux maxima as shown in Fig. 5 will still take place. If $L$, $L_1$ and $L_2$ were all *zero* the phase angles would be 90 degrees, and no cumulative effect would result.

is from $C$ to $D$ in Fig. 2, so that all terms involving a current must be plotted with reversed sign.

The curves of Fig. 5 show:

1. That part of the induced e.m.f., $2e_3$ which consists entirely of odd harmonics. For simplicity it is shown as a sine curve.
2. The second harmonic component of $2e_3$.
3. The mutual flux which induces the e.m.f. (1).
4. The mutual flux which induces the e.m.f. (2).
5. The total mutual flux, which has a greater maximum in the direction $DC$ than in the direction $CD$.

For the sake of simplicity, only the second harmonics in e.m.f. and flux are shown in Fig. 5, but a little thought will show that the effect of all the higher even harmonics is to increase the peak in the flux wave in the direction $DC$.

Since, then, the existence of a small peak in the magnetizing current wave due to slight magnetic unbalance of the phases introduces even harmonics into the flux in such a way as to increase the existing difference between the positive and negative flux maxima, it follows that an additional increase of the magnetizing current peak will take place which will again increase the even flux harmonics. In other words, we have the possibility of a cumulative peaking effect in the current $i_1$; this peak can only attain a permanent steady value if the constant term in the analysis of $i_1$ is cancelled by other consequent constant terms in the remaining terms of equations (**12a**) and (**12b**).

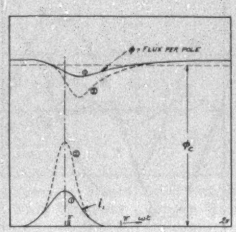


FIG. 6—SHOWING THE EFFECT OF ARMATURE REACTION, WHEN AN UNSYMMETRICAL PEAK IN THE CURRENT $i_1$ IS PRESENT, ON THE TOTAL FLUX PER POLE

*Armature Reaction.* The effects of armature reaction may best be studied by considering the load currents, $I_1$ and $I_2$, and the current $i_1$ separately.

Since the armature has a drum winding the portions $AC$ and $DB$ will not be isolated from each other as is shown in the diagrammatic representation of the armature circuits in Fig. 2, nor will the portions $CB$ and $AD$ be isolated from each other. If we assume that the winding has full-pitch coils the conductors which carry the current $c_4$ in Fig. 2 are situated so that half of them lie in the segment $AC$ and half in the segment $BD$ of the armature surface, and similarly the current $c_2$ flows in conductors which are equally distributed over the same two sections. The magnetomotive forces of the conductors on the armature which actually lie between $A$ and $C$, and between $D$ and $B$, are therefore the same as if these conductors all carried a current equal to $\frac{c_2 + c_4}{2}$, and similarly the m.m.fs. due to the currents $c_1$ and $c_3$ are the same as if all the conductors on the sections $CB$ and $AD$ of the armature carried currents equal to $\frac{c_1 + c_3}{2}$. Now we have:

$$\frac{c_1 + c_3}{2} = \frac{(I_1 + I_2)}{4} + i_1$$

and

$$\frac{c_2 + c_4}{2} = \frac{(I_1 + I_2)}{4} - i_1$$

so that the armature reaction due to the load currents $I_1$ and $I_2$ considered alone is the same as if a current equal to $\frac{I_1 + I_2}{4}$ flowed in each of the parallel paths of the armature. In other words, it is exactly the same as that in a simple d-c. generator with an armature current of $\frac{I_1 + I_2}{2}$ amperes.

The effect of this armature m.m.f. is merely to distort the field flux. Its only results will be to retard the e.m.f. $(e_1 - e_2)$, which will clearly pass through its zero values later if the flux is distorted by the cross-magnetizing effect of the load currents, and also to introduce certain odd harmonics into the wave form of this e.m.f.

Turning now to the armature reaction due to the current $i_1$, which is practically the magnetizing current of the balancer, the general effect is the same as that in a single-phase alternator supplying current to a highly reactive load. The magnetic axis of the armature due to this current is always along the line of the tapping points, and since the maximum value of the current occurs when this axis is practically coincident with that of the poles, it is clear that the conditions are favorable for a maximum reaction on the main flux. From a consideration of the actual direction of the current in the armature, it can be seen that the effect is always demagnetizing except when the tapping points are at the brushes, when the reaction is zero. We thus have a pulsating demagnetizing effect, as in a single-phase alternator as mentioned above.

If $i_1$ were a normal symmetrical magnetizing current in the balancer its armature reaction would be too small to be of any importance, but if it has large peak values once a cycle, due to a cumulative magnetic unbalance, it follows that the demagnetizing effects in the two halves of the cycle will not be the same. Assuming that a peak in $i_1$ takes place in the first half-cycle, the total flux per pole will not be constant but will vary in the manner shown in Fig. 6, (in this sketch the demagnetizing effect in the second half-cycle is neglected, as it is very small). If the variation in flux were exactly proportional at every instant to the demagnetizing m.m.f., the dip in the flux wave would be symmetrical about the ordinate $\frac{\pi}{2}$, but due to hysteresis the change in flux takes place later than the corresponding change in m.m.f., and due to the same cause the flux does not increase to its normal value again until some time after the peak in $i_1$ has disappeared.

This decrease in flux will naturally react on the main field winding, in which e.m.fs. will be induced in such a way as to cause an increase in field current which will follow the variation of $i_1$. For simplicity the field circuit has been omitted from the circuits of Figs. 1 and 2, but actually it forms a coupled circuit with the armature, and the field current divides equally in the two armature paths. Its omission does not introduce any error in the discussion, since the field current is small and has only a very small variation, and further any mutually induced e.m.fs. cannot contain any constant terms since they are always associated with the differential coefficient of a current.

This variation of the total flux per pole is verified by the oscillograms Nos. 13 and 14, which show respectively the e.m.f. induced in a search coil placed round a main pole shoe, and the actual field current of the machine, under conditions where a large peak in $i_1$ was present. It will be noticed in oscillogram No. 13 that the search coil e.m.f. passes through zero later than the instant when the peak is a maximum, and that the generation of the e.m.f. continues some time after the peak has disappeared.

The flux per pole, instead of being given by a constant, must now be expressed by a Fourier series:

$$\text{Flux per pole} = \phi = \phi_c - \phi_1 \sin(\omega t - \psi_1) + \text{higher harmonics} \tag{17}$$

The general form of equation (**17**) may easily be verified by inspection of the flux curve in Fig. 6. The phase angle $\psi_1$ is less than $\frac{\pi}{2}$.

Now the e.m.f. $(e_1 - e_2)$ generated between the points $C$ and $D$ will be given, very nearly, by:

$$(e_1 - e_2) = K\,\phi \cos \omega t \tag{18}$$

(neglecting higher harmonics, assumed small, in the periodic factor of $K\phi$).

Substituting for $\phi$ from equation (**17**), we obtain:

$$(e_1 - e_2) = \frac{K\phi_1}{2}\sin\psi_1 + K\phi_c\cos\omega t - \frac{K\phi_1}{2}\sin(2\omega t - \psi_1) + \text{etc.} \tag{19}$$

The first term of (**19**), it will be noticed, is a constant, which we shall call $E_c$.

The higher harmonics in the expression for $\phi$ in (**17**) do not give rise to any constant terms in $(e_1 - e_2)$; for instance, let there be an $n$th harmonic given by

$$\phi_n \sin(n\omega t - \psi_n)$$

then this introduces a term in the expression for $(e_1 - e_2)$ equal to

$$K\phi_n \sin(n\omega t - \psi_n)\cos\omega t$$

$$= \frac{K\phi_n}{2}[\sin\{(n+1)\,\omega t - \psi_n\} + \sin\{(n-1)\,\omega t - \psi_n\}]$$

and this clearly has a constant term only if $n = 1$.

If any higher harmonics exist in the periodic factor of $K\phi$ in equation (**18**), these will introduce constant terms into $(e_1 - e_2)$ when associated with like harmonics in equation (**17**), but these terms will be small compared with $E_c$, and we may simplify the discussion without introducing any error by neglecting them.

We see, then, that if a peak exists in $i_1$ in the first half-cycle, this will cause a constant term

$$E_c = \frac{K\phi_1}{2}\sin\psi_1$$

in the expression for $(e_1 - e_2)$.

If such a peak exists in the current $i_1$, the Fourier series for $i_1$ will contain a constant term (see equations (**15**) and (**16**)):

$$I_c = I_{m0} - I_0 \tag{20}$$

The condition for the existence of a steady peak in $i_1$, if $R_3$ is equal to $R_4$, is then:

$$I_c = \frac{E_c}{R_a + R_b} \tag{21}$$

which satisfies the condition that the expression for $2e_3$, as given by equations (**12a**) and (**12b**), shall contain no constant term.

*Conditions for the Growth of the Peak in the Magnetizing Current.* The conditions under which a cumulative growth of magnetic unbalance may take place can now be formulated. We have already seen that if there is an initial magnetic unbalance in the two phases, however small, this will result in a small peaking effect in the magnetizing current of the balancer which will introduce even harmonics into the wave-form of the mutual flux in such a way as to increase the difference between the positive and negative flux maxima. This will again cause a greater peak in $i_1$, so that the effect tends to be cumulative. It must, however, be governed by the condition that no constant term can exist in the e.m.f. $2e_3$ under steady conditions.

The constant term $E_c$ depends on the existence of a peak in the current $i_1$, so that we may put:

$E_c = f(I_c)$ (*i. e.*, a function of $I_c$) and (**21**) becomes:

$$I_c = \frac{f(I_c)}{R_a + R_b} \qquad (22)$$

Now if the various factors governing (**22**) are such that, for all values of $I_c$ greater than zero, $I_c$ is greater than $\frac{f(I_c)}{R_a + R_b}$, then the only possible steady condition is given by:

$$I_c = 0$$

and the only possible magnetic dissymetry in the core is that which will make $I_{m0} = I_0$ (equation (**20**)).

$I_c$ is in general very small, so under these conditions no appreciable peaking effect can take place.

On the other hand, if the right-hand term of (**22**) is the greater for small values of $I_c$, the latter will increase in an attempt to satisfy the condition of this equation, so that the cumulative peaking of $i_1$ will take place.

Before proceeding further, it may be helpful to consider the analogous case of the building up of voltage in a d-c. shunt generator, in which an initial residual voltage causes a small field current which in turn produces more voltage, and so on, the growth being limited by the fact that the field current and the terminal voltage are bound together by a double relation; first that the field current multiplied by the field resistance must be equal to the voltage, and secondly that the field current and the voltage are relatively fixed by the magnetization curve of the machine. In order that the voltage may grow, that produced by a certain field current must be more than that required to send that current through the resistance of the field winding, and as soon as these two voltages become equal a stable value is obtained. This is shown graphically in Fig. 7, where the line $R$ gives the relation between volts and field current as required by the field resistance, and $M$ is the magnetization curve of the machine (corrected for the small armature drop due to the field current). The voltage given by the magnetization curve $M$ tends to cause field current, while the potential difference across the field, given by $R$, tends to resist the flow of field current, and for an initial growth of field current the "causing voltage" must be greater than the "resisting voltage." Further, if the effect is to stop at some stable value, then the ratio $\frac{\text{causing volts}}{\text{resisting volts}}$ must decrease as the field current increases until it reaches unity, at which point a balance will be obtained and a steady field current and voltage will result. This stable value is shown at the point $P$, where the two curves cross.

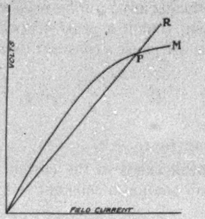


FIG. 7—ILLUSTRATING THE PHENOMENON OF THE BUILDING UP OF VOLTAGE IN A SHUNT GENERATOR

It is interesting to note that if the natural laws of magnetic induction were such that the curve $M$ curved the other way the effect would be unstable and the generated voltage would tend to increase indefinitely.

In the case under consideration the "peak value of $i_1$" is analogous to the field current, and the "constant terms" take the place of the voltages in the above discussion. The "causing" constant term is that in $(e_1 - e_2)$, while the "resisting" constant term is that in $i_1$. It will therefore be necessary to determine the relations between the peak value in $i_1$ and the two constant terms which it introduces.

### *Definition of "peak value of $i_1$"*

The term "peak value" as used in the following is taken to be the *difference* of the positive and negative maxima of the current. That is to say, if the magnetizing current is normal and has equal positive and negative maxima, the "peak value" is zero. This is consistent with the fact that such a current would have no constant term in its analysis, and would not cause any constant term in $(e_1 - e_2)$.

For large peak values the smaller maximum value is almost negligible when compared with the greater, but when considering the initial stages of the growth it is important.to keep the above definition in mind.

If now a number of curves such as that of $i$ in Fig. 4 be plotted for different values of the second harmonic in the flux wave, making use of the magnetization curve of the sheet steel of which the core is built up, for each curve we obtain a definite peak value and a definite constant term. The current wave so plotted is true magnetizing current, so that the constant term is that given by $I_{m0}$ in equation (**16**). Actually, of course, higher even harmonics are present in the flux waves, but the general form of the variation may be deduced as above. If we plot the values of the constant term on a base of "peak value," we obtain a curve, which is practically linear, shown as $I_{m0}$ in Fig. 8.

The accurate relationship between the constant term $E_c$ and the peak value of the current is more difficult to obtain, but the general shape of the curve may be deduced. We see from equation (**19**) that $E_c$ depends both on the amplitude $\phi_1$ of the fundamental component of the flux per pole and on the magnitude of the phase angle $\psi_1$. As the peak value of the magnetizing current increases, the peak itself becomes sharper and requires a relatively smaller fundamental and relatively larger higher harmonics in its analysis. This effect is transmitted to the time variation of the flux per pole, as is shown in Fig. 6 where the curves (**2**) show the sharper peaking produced by a higher peak value of $i_1$. It is evident then that the ratio

$$\frac{\phi_1}{\text{Peak value of } i_1}$$

will decrease as the peak value of $i_1$ increases. The phase angle $\psi_1$ will not undergo any appreciable change, so that it follows that the ratio

$$\frac{E_c}{\text{Peak value of } i_1}$$

will also decrease as the peak increases. At the same time, however, it should be noticed that, as the peak increases, the actual peak decrease in flux is apt to increase slightly more rapidly, due to the fact that a steeper part of the saturation curve of the magnetic circuit of the machine is reached. The curve of $\dfrac{E_c}{R_a + R_b}$ in Fig. 8 therefore bends over more rapidly at first, straightening out slightly as the peak value increases.

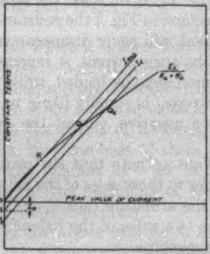


FIG. 8—ILLUSTRATING THE CONDITIONS FOR THE GROWTH OF THE PEAK IN THE CURRENT $i_1$

The curves $I_{m0}$ and $\dfrac{E_c}{R_a + R_b}$ of Fig. 8 together give the possibility of a magnetic unbalance with no out-of-balance current at all. The point $P_1$ where they cross gives the stable value of magnetizing current peak under these conditions. (See oscillogram No. 1.)

When an out-of-balance current $(I_1 - I_2)$ flows, the constant term which must be plotted in Fig. 8 for the current is $I_c = I_{m0} - I_0$ (equation (**20**)), where $I_0$ is proportional to $(I_1 - I_2)$.

To obtain the conditions for a particular value of $(I_1 - I_2)$, $OO_1$ is set off, as shown in Fig. 8, equal to $I_0$, and the curve $I_c$ is drawn parallel to the curve $I_{m0}$ with the point $O_1$ as origin. The point of intersection $Q_1$ of this curve and that of $\dfrac{E_c}{R_a + R_b}$ gives the final steady value of the peak current.

If a series of such curves be drawn, $O_2Q_2$ etc., the points $Q_1$, $Q_2$, etc., will give the steady peak values corresponding to out-of-balance currents proportional to $OO_1$, $OO_2$, etc., and it is seen from the general shape of the curves that the peak value increases less rapidly than the out-of-balance current.

It is also clear from Fig. 8 that if $(R_a + R_b)$ is increased the result will be a decrease in peak value for any one value of out-of-balance current, and conversely, if $(R_a + R_b)$ is decreased the peak values will be larger than before. (See oscillograms Nos. 15 and 16.)

*Effect of Unbalanced Resistance of the Balancer Phases.* If, in Fig. 2, $R_4$ is greater than $R_3$, it follows from equations (**12a**) and (**12b**) that the current $i_1$ must be such as to contain a constant term which will cancel the term so introduced in addition to $E_c$. Its value, instead of being given by equation (**21**), will now be governed by:

$$I_c = I_{m0} - I_0 = \frac{E_c}{R_a + R_b} + \frac{R_4 - R_3}{R_a + R_b} \cdot \frac{(I_1 - I_2)}{2} \quad \textbf{(22)}$$

so that the peak value of $i_1$ will be greater than before.

On the other hand, if $R_4$ is less than $R_3$, it is evident that the constant term in $i_1$, and consequently the peak value, will be less than when the resistances are balanced. Further, the unbalance of resistance may introduce such a large negative term in equation (**22**) that the current $i_1$ will have to develop a constant term of opposite sign to that originally present, resulting in a complete reversal of the peak, which will appear in the opposite direction and during the second half of the cycle. (That this is possible may be seen from Fig. 4; a flux given by $\phi = 80 \sin \omega t + 25 \cos 2\omega t$ would have a negative maximum greater than its positive maximum, and consequently the peak in the magnetizing current would be negative and in the second half of the cycle.)

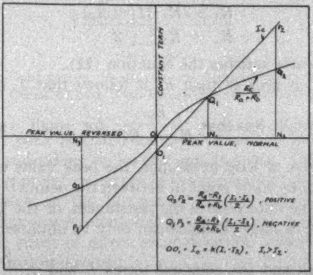

$I_c$
$P_2$
$Q_2$
CONSTANT TERM
$\frac{E_c}{R_a+R_b}$
$Q_1$
PEAK VALUE, REVERSED
O
$N_1$
$N_2$
$N_3$
PEAK VALUE, NORMAL
$O_1$
$Q_3$
$P_3$
$Q_2P_2 = \frac{R_4-R_3}{R_a+R_b}\left(\frac{I_1-I_2}{2}\right)$, POSITIVE
$Q_3P_3 = \frac{R_4-R_3}{R_a+R_b}\left(\frac{I_1-I_2}{2}\right)$, NEGATIVE
$OO_1 = I_0 = k(I_1-I_2)$, $I_1>I_2$.

FIG. 8A—ILLUSTRATING THE EFFECT OF UNBALANCED PHASE RESISTANCE ON THE PEAK IN THE CURRENT $i_1$

This effect is shown graphically in Fig. 8A, for a given value of out-of-balance current $(I_1 - I_2)$. The curves of $I_c$ and $\dfrac{E_c}{R_a + R_b}$ are continued back into the negative quadrant as shown, for if the peak reverses it is clear that these constant terms must reverse as well. It should be noticed that the curve of $I_c$, when reversed, starts as before at the point $O_1$, since $OO_1$ is equal to $(I_1 - I_2)$ multiplied by some constant and only reverses if the unbalanced current reverses. In other words, for the condition of a reversed peak we have:

$$-I_c = -I_{m0} - I_0$$

The normal peak value, when $R_3$ and $R_4$ are equal, is equal to $ON_1$, corresponding to the point $Q_1$. If, however, $R_4$ is greater than $R_3$, the peak will be equal to $ON_2$, corresponding to the points $P_2$ and $Q_2$ where $Q_2P_2$ is equal to

$$\frac{R_4 - R_3}{R_a + R_b} \frac{(I_1 - I_2)}{2}.$$

This clearly satisfies the equation (**22**).

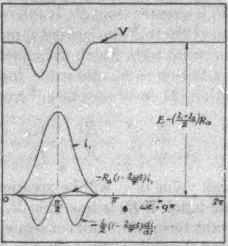

V
$E-(\frac{I_1+I_2}{2})R_a$
$i_1$
$-R_a(1-\frac{2\omega t}{\pi})i_1$
0
$\frac{\pi}{2}$
$\pi$
$\omega t = q\pi$
$2\pi$
$-\frac{L}{2}(1-\frac{2\omega t}{\pi})\frac{di_1}{dt}$

FIG. 9—PULSATIONS IN THE TERMINAL VOLTAGE OF THE MACHINE DUE TO A PEAK IN THE CURRENT $i_1$ OCCURRING WHEN $q = ½$

If $R_3$ is greater than $R_4$ it follows that $I_c$ must be algebraically less than $\frac{E_c}{R_a + R_b}$; for small values of resistance, or load unbalance, the peak value will now be given by some point in between the points $O$ and $Q_1$, but if the difference in the resistances, or the load unbalance, is large, balance can only be obtained if both the peak and the constant terms $I_c$ and $\frac{E_c}{R_a + R_b}$ reverse. This condition is given by the points $Q_3$ and $P_3$, where $Q_3P_3$ is equal to

$$\frac{R_4 - R_3}{R_a + R_b} \frac{(I_1 - I_2)}{2}$$

which is now negative. The peak value is equal to $ON_3$, which is also negative, but numerically less than $ON_2$.

The actual existence of reversed peaks due to resistance unbalance is seen in oscillograms Nos. 4, 9, and 10.

*Effect When the Negative Side of the System Has the Heavier Load.* In the whole of the above discussion it has been assumed that the positive side of the system is the more heavily loaded. If $I_2$ is greater than $I_1$ the actual direction of the out-of-balance current will be towards the center of the balancer, instead of outwards from it, and the initial magnetic unbalance will set up a small flux in the direction $CD$ (Fig. 2); this will start a peak in the magnetizing current in the second half of the cycle instead of in the first, and this peak will introduce even harmonics into the balancer flux which will produce further peaking of $i_1$. Otherwise the effect will be exactly the same as when the positive side was the more heavily loaded.

It follows, since the sign of the peak is opposite to that in the first case, that the signs of the constant terms $(I_{m0} - I_0)$ and $E_c$ will also be reversed, and since the sign of $(I_1 - I_2)$ is reversed the equation (**22**) still holds. If, therefore, in Fig. 2 the resistance $R_4$ is greater than $R_3$, the peak will never disappear and change sign as the out-of-balance current is increased, no matter which side is more heavily loaded, while if $R_3$ is greater than $R_4$ the reversal is equally likely to occur whether the positive or negative side of the system has the heavier load.

It is important to note that the resistances $R_3$ and $R_4$ in Fig. 2 refer to those sides of the balancer which are connected to the armature taps $C$ and $D$ respectively, and not to the two sides of the balancer as considered apart from the machine.

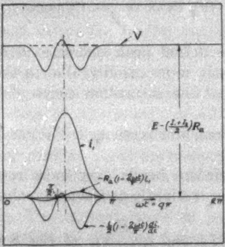

V
$E-(\frac{I_1+I_2}{2})R_a$
$i_1$
$-R_a(1-\frac{2\omega t}{\pi})i_1$
0
$\frac{\pi}{2}$
$\pi$
$\omega t = q\pi$
$2\pi$
$-\frac{L}{2}(1-\frac{2\omega t}{\pi})\frac{di_1}{dt}$

FIG. 10—PULSATIONS IN THE TERMINAL VOLTAGE OF THE MACHINE DUE TO A PEAK IN THE CURRENT $i_1$ OCCURRING WHEN $q$ IS SLIGHTLY GREATER THAN ½

*Pulsations in the Terminal Voltage.* The voltage drop between the brushes $A$ and $B$ due to the flow of the armature current is given by equation (**1**). If we substitute in this expression the value of $i_2$ as given by equaton (**4**) we obtain:

Drop due to armature currents =

$$D_{ab} = \frac{(I_1 + I_2)}{2} \cdot R_a + \left(R_a i_1 + \frac{L}{2} \frac{di_1}{dt}\right)\left(1 - \frac{2\omega t}{\pi}\right)$$

The terminal voltage $V$ $(= V_1 + V_2)$ is therefore $= E - D_{ab}$, where $E = e_1 + e_2$, the voltage generated in the armature between the brushes.

If we assume that $E$ is approximately constant (actually it decreases slightly due to armature reaction when a peak in $i_1$ occurs) the wave form of $V$ will be given by the curves in Figs. 9 and 10, for the case when a peak in $i_1$ occurs in the first half cycle. Fig. 9 assumes that the peak occurs when $q = \frac{1}{2}$, but when the machine is loaded the instant when $(e_1 - e_2)$ is zero is later than $q = \frac{1}{2}$ due to the distorting of the field by the cross m.m.f. of the armature. Consequently the peak in $i_1$ will occur a little later than $q = \frac{1}{2}$, with the result shown in Fig. 10, where it is seen that the value of $V$ actually rises above its normal value at one point.

In these two diagrams the effects of $i_1$ during the parts of the cycle when it has a normal value are neglected in comparison with the effects of its peak. It should be noted that while the time-base of these diagrams, $\omega t$, is continuous, the relation $\omega t = q\pi$ is only true if $t$ starts from zero at the beginning of each half cycle, since $q$ is never greater than unity.

By combining the above expression for $(V_1 + V_2)$ with equation (**9**), it can easily be shown that both $V_1$ and $V_2$ will have pulsations similar in form to those shown in Fig. 10. Actual oscillograms of these voltages are shown in oscillograms Nos. 6, 7, and 12.

## TEST RESULTS

The machine tested was a 6-pole, 75-kw., 1,200-r.p.m., 125-250-volt, three-wire generator with a full-load current of 300 amperes. The static balancer was of the two-phase type, mounted externally to the machine. It was rated for a maximum out-of-balance current of 75 amperes. The armature resistance of the machine, $R_a$, was approximately 0.015 ohm, while that of the balancer, $R_b$, was approximately 0.065 ohm. These do not include the equivalent resistances of the various brush contacts, which introduce considerable variation into the values of resistance as used in the discussion of the phenomena. For this reason accurate quantitative tests were not attempted, the sole purpose being to examine experimentally the general analytical conclusions of the paper.

It was found that very large peaks occurred in the balancer phase currents when the machine supplied unbalanced loads, and it was further found that these peaks depended only on the unbalanced load and were independent, excepting for the effects of the cross m.m.f. of the armature, of the balanced load on the machine. The generator was compound-wound, but the phenomena were found to be independent of the use of the series winding.

The insertion of the oscillograph shunt in the balancer leads introduced an unbalance in the resistance of the two phases of the balancer, with the interesting results shown in the oscillograms. These are consistent with the previous theoretical discussion, as are the pulsations in the terminal voltages of the system.

The machine was driven by a 6-pole synchronous motor at 60 cycles, this a-c. supply being also used to drive the small synchronous motor which actuated the oscillating mirror for the "time base" on the oscillograph. When the waves were watched on the viewing-screen it was found that several seconds elapsed before the peaks became steady after a change of load. Indeed, when the load was instantaneously changed from a positive to a negative unbalance or *vice versa*, the previous peak persisted for a few moments before reversing and taking up its new steady value. This bears out the cumulative nature of the phenomena, and their dependence on the flux-waves in the balancer core. These flux-waves, containing strong even harmonics, give the effect of direct magnetization, which cannot reverse instantaneously.

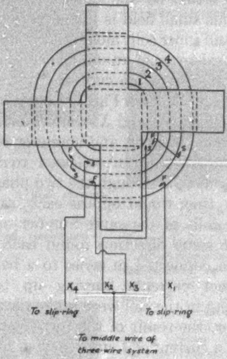


FIG. 11—CONNECTION DIAGRAM AND ARRANGEMENT OF CORE AND COILS OF THE TWO-PHASE STATIC BALANCER

It was also found that the ordinary magnetizing current, with no unbalanced load, showed evidence of unsymmetrical flux variation (see oscillogram No. 1).

*Magnetic Unbalance of Balancer Phases.* The two-phase static balancer has its coils wound concentrically on the center leg of a five-leg G. E. distribution transformer core. The winding is in the form of four coils of two layers each, as in Fig. 11. The coils 1 and 4 comprise one phase, while coils 2 and 3 comprise the other. The exact calculation of the magnetic field set up across the area of the inner leg by equal currents flowing in the two phases in opposite directions is a matter of some diffculty, and is not attempted here. If the coils are equally spaced it will not, however, be zero, as may easily be seen if the magnetic field be calculated at the center of four equally spaced concentric short solenoids, in which the current is the same in each coil and in such a direction that the inner and outer coils oppose the two center ones.

The actual windings of the balancer tested may be represented approximately by four concentric solenoids of circular section 4.875 in. long and with radii equal to 2.201 in., 2.534 in., 2.866 in., and 3.199 in., each having 34 turns. If a current $I$ amperes flows through each coil in such a way that the outer and inner oppose the magnetic action of the two central ones, the magnetic field at the central point of the arrangement will be equal to:

$$H_c = 0.0244\, I \text{ oersteds}$$

(If they all magnetized in the same direction the field at the center would be about 23.6 $I$ oersteds). The direction of this small field is the same as that set up by the outer and inner coils alone.

The actual existence of an unbalance in the magnetic effect of the phases on the core was tested as follows. The leads $X_1$ and $X_3$ (see Fig. 11) were connected together and the leads $X_2$ and $X_4$ were connected through a rheostat, circuit breaker, and ammeter to a source of direct current. Any current allowed to flow in this arrangement will flow through the two phases in such a direction that they would oppose each other magnetically. Search coils of the same number of turns were wound in the same direction round each of the four outer legs and connected in series to a ballistic galvanometer. Direct currents varying up to about 60 amperes flowing in the coil were broken by opening the circuit breaker, the result of the test showing that the flux set up by a current of $I$ amperes was approximately equal to 10 $I$ maxwells.

This result gives a figure which is too low on account of the fact that the current was broken but not reversed, so that there was a possibility of some residual magnetism. The galvanometer flings were, however, exactly proportional to the current broken, over the range of the tests. Further, the flux measured was the total flux in the four outer legs, which is less than that in the center leg due to leakage.

In interpreting the above result, it should be remembered that the permeability of the core with such a weak magnetizing force would be very low, possibly of the order of 50. The test showed quite definitely that a magnetic unbalance of the phases did exist, and the analytical discussion of the phenomena only presupposes a small unbalance. Theoretically any unbalance, however small, would be sufficient to start the cumulative growth of the peaks in the magnetizing current, provided the normal maximum flux density in the core lies on a part of the magnetization curve which is only slightly curved towards the saturation region. The maximum flux density in the center leg of the balancer tested, under conditions of symmetrical flux-variation was 70.4 kilolines per square inch, at which point the magnetization curve is by no means straight.

## OSCILLOGRAMS

In order to study the wave form of $i_1$ the oscillograph shunt was inserted in one or other of the leads between the slip-rings and the balancer. The lead to the slip-ring nearer to the commutator will be called "lead $A$," while the lead to the slip-ring nearer to the end of the shaft will be called "lead $B$."

The wave-forms thus obtained are those of the currents

$$\frac{I_1 - I_2}{2} + i_1 \text{ and } \frac{I_1 - I_2}{2} - i_1$$

(see Fig. 1).

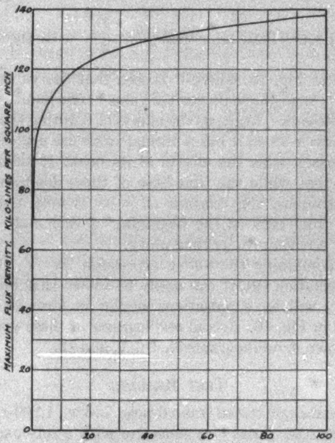


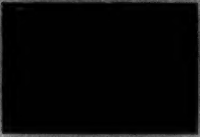
FIG. 12—RELATION BETWEEN VALUE OF PEAK IN THE CURRENT $i_1$ AND THE MAXIMUM FLUX DENSITY IN THE CORE OF THE BALANCER

The first half of the cycle as understood in the discussion appears as the second half in the oscillograms. The choice of which shall be considered as the first half of the cycle is entirely arbitrary and there is no inconsistency in the results.

It was found that, when the oscillograph shunt was in the lead $A$, the peak reversed at some value, positive or negative, of $(I_1 - I_2)$, but when the shunt was placed in the lead $B$ no reversal ever took place.

## CONCLUSION

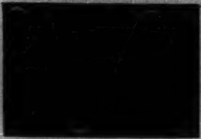
The most important fact which comes to light in these results is that, although the balancer windings are designed to give very nearly perfect magnetic balance of the phases, saturation phenomena in such a machine may grow to proportions immensely greater than would at first sight be expected. The large magnetizing current peaks give evidence of very high values of maximum



No. 1—No Unbalanced Load, and Mid-Point of Balancer Disconnected from Three-Wire System

Shows magnetizing current in the balancer, and the voltage across the slip-rings

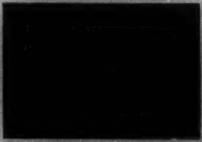
R.m.s. value of current = 0.25 amperes approximately



No. 2—4 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

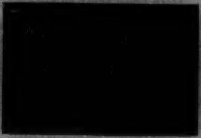
Peak value of current $i_1$ is 6.25 amperes. This is less than normal due to resistance of oscillograph shunt (0.102 ohms) introduced into the balancer circuit



No. 3—37 Amperes Unbalance, Negative Side, 205 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

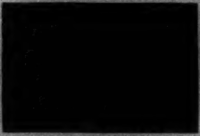
Peak value of $i_1$ is 4.1 amperes, very much reduced by resistance of shunt (0.026 ohms) producing an unbalance of resistance in the balancer phases



No. 4—47.5 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

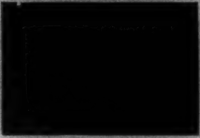
Peak value of $i_1$ is 9.5 amperes, completely reversed due to unbalance of resistances of balancer phases, due to oscillograph shunt (0.026 ohms)



No. 5—4 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and voltage across slip-rings

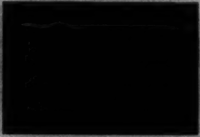
Peak value of $i_1$ is 11.6 amperes, increased due to oscillograph shunt resistance (0.012 ohms) in lead *B*



No. 6—18.2 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and voltage across the loaded side of the system

Peak value of $i_1$, is 27.0 amperes, resistance of the oscillograph shunt 0.026 ohms

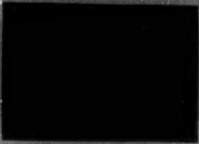


No. 7—63 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and volts across the outside wires of the system

Peak value of $i_1$ is 58 amperes, resistance of shunt 0.0112 ohms

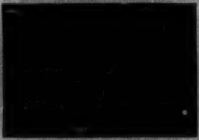
D-c. voltage shows a total variation of 18.5 volts, or 7.4 per cent



No. 8—3.9 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

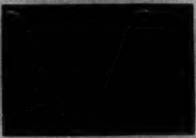
Peak value of $i_1$ is 4.0 amperes. Resistance of shunt 0.102 ohms



No. 9—48.9 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

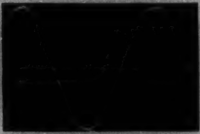
Peak value of $i_1$, is very small, having just reversed. Resistance of shunt 0.026 ohms



No. 10—59.5 Amperes Unbalance, Positve Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

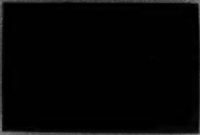
Peak value of $i_1$, is 7.4 amperes, having completely reversed due to shunt resistance, 0.026 ohms, in lead *A*



No. 11—4.0 Amperes Unbalance, Positive, 250 Volts D.C.

Shows current in lead *B* and volts across slip-rings

Peak value of $i_1$ is 7.7 amperes. Resistance of shunt 0.102 ohms

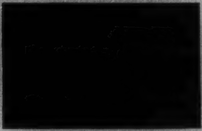


No. 12—50 Amperes Unbalance, Negative Side

Shows total out-of-balance current (lower trace), the oscillograph shunt being put in the neutral wire of the system; and the voltage across the loaded side (upper trace)

The balance leads were connected with no extra resistance in them

The load consisted of a practically non-inductive resistance



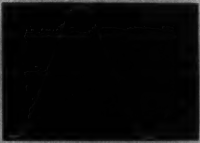
No. 13—76 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *B* and voltage induced in search coil of 30 turns placed around a main pole shoe

The peak value of $i_1$ is 54 amperes

The maximum value of the induced voltage is approximately 0.3 volt. This voltage is due to the decrease in flux which takes place once a cycle due to the armature reaction of $i_1$

It will be noticed that the generation of the e.m.f. persists after the peak in $i_1$ has died to zero



No. 14—76 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows voltage across slip-rings and field current of machine. No extra resistance in balancer leads

The leads from the oscillograph to the slip-rings in this case have been reversed, so that the voltage wave is upside down when compared with the previous oscillograms

The field current is seen to increase at the instant corresponding to the peak in $i_1$ (compare with No. 13)

No. 15—SHOWING EFFECT OF INCREASED RESISTANCE OF BALANCER CIRCUIT

In this case extra resistance was put in both phases of the balancer, the total extra resistance in lead *A* being 0.387 ohms, and in lead *B* 0.402 ohms. The ocillogram shows the current in lead *A* and the voltage across slip-rings for a negative unbalance of 3.14 amperes. (The resistance 0.387 ohms of lead *A* is the resistance of the parallel circuit of the oscillograph current strip and the extra resistance introduced into the phase)

The actual peak value of the current $i_1$ is 2.20 amperes, while the extra peak value, as defined in the paper, is 1.81 amperes

Compare this with No. 2 and No. 5

No. 16—SHOWING EFFECT OF INCREASED RESISTANCE OF BALANCER CIRCUIT

In this case extra resistance was again put in each phase of the balancer, the total extra resistance in lead *A* being 1.75 ohms, (this is the resistance of the parallel circuit of a non-inductive rheostat in parallel with the oscillograph current strip), and that in lead *B* 1.81 ohms

The oscillogram shows the current in lead *A* and the voltage across slip-rings for a negative unbalance of 3.11 amperes

The actual peak value of the current $i_1$ is 1.08 amperes, while the extra peak value, as defined in the paper, is only 0.68 amperes

This should be compared with Nos. 2, 5, and 15, from which it will be seen that an increase of resistance of the balancer phases by approximately the same amount in each phase results in an appreciable decrease of the peak current

flux density, which may be calculated from the results in a very simple manner. In Fig. 12 is shown a magnetization curve for the balancer core in question, giving the maximum flux density in kilolines per square inch on a base of peak magnetizing current. This peak magnetizing current is practically the same as the peak values of $i_1$ as measured on the oscillograms, so that in any of the cases shown the maximum flux density may be at once obtained. Taking the maximum peak value shown, 58 amperes (oscillogram No. 7), the maximum flux density in this case is about 133 kilolines per sq. inch, or very nearly double the value for which the core was designed.

These high values of flux density occur only once a cycle, so that the hysteresis loops are considerably displaced, giving rise to increased core losses in the balancer.*

The current peaks in the balancer windings will also increase the copper losses. Taking the same case of oscillogram No. 7, the r.m.s. value of the balancer phase current shown is 27.5 amperes, while that of the current in the other phase (where the peak adds to the direct current component) is 47 amperes. Under normal conditions, with no peak, the current in each phase would be 31.5 amperes, so that the total copper losses in the balancer windings are increased approximately 50 per cent by the presence of the peak, while the copper losses in the phase carrying the larger r.m.s. current are increased no less than 122 per cent.

It is true that in this particular case the peak value of the current $i_1$ is somewhat greater than under conditions of balanced resistance of the phases, since the introduction of the oscillograph shunt has introduced a resistance unbalance in such a way as to increase the peak, but it is clear that these phenomena may give rise to excessive heating of the balancer if the latter is worked at full out-of-balance capacity for any length of time. There will also be an increase of heating in the armature windings, but since each part of the armature circuit only carries half the current $i_1$ and since the full-load current of the armature is very much greater than that of the balancer this effect will not be of very great importance.

It is evident from equation (9) that if the phase resistances of the balancer are unequal, the presence of a large peak in $i_1$ will affect the voltage regulation of the system. For instance, if $R_4$ is greater than $R_3$ the mean value of $(V_2 - V_1)$ will be reduced, but this is at the expense of a larger peak and consequent larger pulsations in the voltages of the system.

It has already been pointed out, in connection with Fig. 8, that the peak value of $i_1$ can be decreased by increasing the value of $(R_a + R_b)$. A certain increase in the resistance of the balancer windings might, therefore, produce a net decrease in the losses. If it should be considered necessary to remove the effect altogether, the logical method would seem to be the use of a compensating winding in the pole-faces of the machine; this could be made to cancel the armature reaction, and so remove the constant term $E_c$ without which the constant term $I_c$ cannot exist. Under such conditions no cumulative effect would take place.

It would not seem that a low maximum flux density in the balancer core is of very much use in preventing the effect, since the growth of the peak needs only a magnetization curve which is not perfectly straight, and this is inevitable even with very low densities.

In conclusion the author wishes to thank Dr. H. Vickers, of the University of British Columbia, for the interest he has taken and the kind encouragement he has given to the progress of this work.

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# Shaping of Magnetization Curves and the Zero Error Current Transformer

BY A. C. SCHWAGER*
Member, A.I.E.E.
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## ACCURACY LIMITATIONS OF ELECTRICAL ENERGY MEASUREMENTS

THE sale of electric power constitutes the basic income of all electric power companies; its purchase is an item of major importance to the consumer. The measurement of power is universally performed by the watthour meter. The amount of capital involved in these transactions makes necessary the measurement with highest possible accuracy. For domestic uses, the accuracy is given by that of the watthour meter, which can be built with errors in the order of one tenth of one per cent. Conditions are different in the case of high-voltage measurements, where the accuracy is given by the combination of watthour meter, current, and potential transformer. The phase angle error of the current transformer is of primary influence. If the ratio error and the errors in the potential transformer are neglected, the following error in a single-phase system operating at a load phase angle $\varphi$, results

$$\Delta P_{per\ cent} = 0.029\ \theta' tg\varphi$$

A current transformer with a phase angle error of 40 minutes at a system power factor of 0.2 causes an error of 5 per cent in power measurement. Such errors can easily occur in the measurements on transformers and induction motors at no load; they assume additional importance with the exchange of power at low system power factor over the steadily increasing number of system interconnections.

## REQUIREMENTS OF THE IDEAL CURRENT TRANSFORMER

1. *Accuracy.* This condition can only be remedied by the more complete elimination of the current transformer errors; these should be reduced to values as they exist in watthour meters. Accuracy limits of 0.1 per cent in ratio and a few minutes in phase angle are required over the entire range of secondary current, that is from 0.5 to 5 amperes.

2. *Burden Capacity.* The capacity shall be high, possibly of the magnitude of 50 volt amperes.

3. *Insulation and Overload Capacity.* In view of the attention which has been given this problem in the past, it will not be necessary to explain it in detail; it is generally recognized that the bushing type current transformer would represent the ideal solution, if it could in addition fulfil requirements 1 and 2.

For this reason a great amount of effort has been spent to improve it with the following major methods now available.

1. Use of high permeability steel.[1,2,3]
2. Brooks' two-stage principle.[4]

Fig. 1 shows the calculated ratio and phase angle curves for various 200/5 ratio bushing type current transformer of 15 in. inside diameter, 18.5 in. outside diameter and 7 in. core height operating at a burden of 15 volt amperes, 100 per cent power factor. *A* represents the ordinary silicon iron core transformer, *B* the high permeability steel core type and *C*, the Brooks' two-stage type used for single element instrument application. None of these transformers meets the accuracy specified in 1 and they are not applicable for metering purposes.

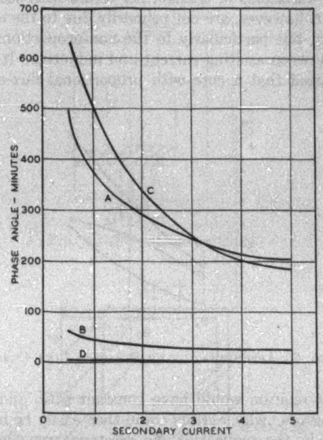

FIG. 1—PHASE ANGLE ERRORS, 200/5 RATIO, 15 IN. INSIDE DIAMETER BUSHING TYPE CURRENT TRANSFORMER, BURDEN 15 VOLTAMPERES 100 PER CENT POWER FACTOR

A—Silicon-iron core
B—Nickel-iron core
C—Brooks' two stage
D—Constant permeability core

Curve *D* pertains to a new method of improvement described in this article using a core combination of apparent constant alternating current permeability which makes possible the construction of high-voltage, high-accuracy low-ratio bushing type transformers and which reduces the errors of wound type transformers to less than one per cent of their present values. This is accomplished without structural changes to the ordinary transformer; silicon iron is used as core material.

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*Pacific Electric Mfg. Corp., San Francisco, Calif.

1. For references see Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

The explanation of the principle of operation is based on the theory of shaping of magnetization curves.

## SHAPING OF MAGNETIZATION CURVES

*The Constant Permeability Transformer.* Since the magnitude of the exciting current is the prime cause of all transformer errors, a reduction in its value is often considered the only means of reducing them. This reasoning is fundamentally wrong as proven, for instance, by the fact that Brooks's two-stage principle for certain conditions is more effective than methods which are based on a simple reduction of the exciting current such as is obtained by the use of nickel iron alloys.

The variations of transformer errors with secondary current, however, are not primarily due to the exciting current, but particularly to the non-proportional relation between exciting current and induction. It is well recognized that a core with proportional flux-exciting current relation would have constant ratio and phase angle errors,[5] which errors could then easily be brought to zero by the application of a resistance or a condenser and by turn compensation. However, the means of producing iron with proportional flux-exciting current relation or expressed otherwise—"with a constant permeability," are not available. It is apparent, however, that a material of constant permeability would be the final solution to the current transformer problem and the following investigation will be along this line and describe the method of obtaining a core of constant permeability.

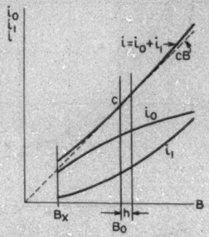


Fig. 2—Approximation of Straight Line Curve

Whereas the actual induction-magnetizing current relation is given by curve $i_o$ Fig. 2 the dotted line represents the necessary relation and is mathematically formulated by

$$i_m = \text{constant } B \tag{1}$$

In most technical applications, it will be sufficient for (1) to hold true from values $B_x$ to ten times $B_x$, which range corresponds to the normal operating range of current transformers. Cores of various transformers, naturally, will work over different ranges of induction, corresponding to different initial inductions $B_x$, but for each range, independent of the starting point, complete proportionality is required up to ten times $B$. The $B - i_m$ relation outside this range is not important and no specification will be set up for it, the closer it approaches proportionality, however, the more valuable it will be.

*Molecular Theories of Magnetization.* The problem requires the production of a magnetization curve. Although technical research, by means of alloys and by heat treatment has produced magnetization curves different from the ordinary silicon iron curve, these synthetic methods have not been able to produce the required straight magnetization curve. On the other hand, a solution from the purely scientific side seems too remote although great advancements have been made in the last few years in the explanation of ferromagnetism.

In the following an attempt toward a solution is made by the use of one distinct principle of the molecular theories of magnetization.

Langevin's theory of paramagnetic substances calculates by means of the classical mechanics the magnetization curve and obtains functions which closely approximate those found by experiment. The value of the magnetic induction for each value of the magnetizing force is obtained as the summation of the contributions of the elementary magnets.

Ewing's theory has attempted to explain the magnetization curve of iron as the sum of the magnetization curves of elementary atomic magnets or complexes.

Disregarding the question of the validity of the above theories, they both reveal a principle by which magnetization curves can be produced: by a summation of the magnetization curves of elementary complexes. In the following technical applications this procedure will be denoted as "artificial shaping of magnetization curves."

The elementary complex will be replaced by a small particle of magnetic material, whose magnetization curve will correspond to that of the elementary complex. A great number of particles with individually different magnetization curves will then be investigated in regard to the resulting curve. In particular, it should be possible to choose sizes and curves of the particles in such a way that the resultant magnetization curve is a straight line. The selection of the individual curves for the synthesis of a given function $i = f(B)$ is of great importance, they should present a sufficient functional variety to be of value. It is well known that the magnetization curve of ordinary silicon iron represents a function of continuously varying characteristics. For values of low flux density the curve $i = f(B)$ is concave with regard to the $B$ axis, for higher value it is convex. It cannot be represented as a single function over its entire range, hence it carries in itself the great functional variety required. In the following, a few of the fundamental schemes of shaping of magnetization curves using the silicon iron curve as the basis will be considered; due to the subsequent applications all calculations will be based on alternating currents of a frequency of 60 cycles per second.

## FORMULATION OF MAGNETIZING CURRENT-FLUX RELATION, ADOPTION OF UNIT REFERENCE CORE

In the following, the magnetizing current will be referred to a silicon-iron core of 1 lb. weight and a cross section of 1 sq. in. perpendicular to the lines of force. In a single turn around the smaller cross section neglecting leakage, the following flux-magnetizing current relation exists

*Formula for Low Flux Density.*

$$10 < B < 1{,}000$$

$$i_o = 2.5\,10^{-2}\,B^{0.6} \qquad (2)$$

*Formula for High Flux Density.*

$$3{,}000 < B < 18{,}000$$

The Frohlich-Kennelly relationship[6] states the variation between magnetizing force and induction $B$ for high d-c. fields as follows:

$$\frac{H}{B} = \alpha + \sigma H$$

This relationship holds closely true also for a-c. magnetization curves of silicon iron, giving the following magnetizing current for the unit reference core:

$$i_1/lb = \frac{10}{\dfrac{19{,}300}{B} - 1} \quad 3{,}000 < B < 18{,}000 \qquad (3)$$

## COMBINATION OF A LIMITED NUMBER OF CORES

*Method No. 1.* An ordinary reactor, consisting of a section with a large cross section and of another section with a smaller cross section is representative of this method, see Fig. 3A. For simplicity in calculations a few assumptions will be made. The flux distribution in the small and large cross section will be uniform, leakage flux will be negligible, giving equal total flux in the small and large cross section. The problem thus reduces itself to the considerations of two cores of different cross sections with flux densities inversely proportional to these cross sections. The magnetizing current necessary is equal to the sum of the magnetizing currents which would be required for each section.

As shown in Fig. 3B a unit core of 1 lb. is assumed working at low flux density $B_o$ the magnetizing current $i_o$ thus being given by formula (2). The weight of the core working at high saturation $B_1$ is reduced to $W$ pounds, its current $i_1$, within its limit of application, is given by:

$$i_1 = \frac{10W}{\dfrac{19{,}300}{B_1} - 1} = \frac{10W}{\dfrac{19{,}300}{dB_o} - 1} \qquad (4)$$

Where $d = B_1/B_o$ and is constant.

As shown in Fig. 3B, the cross section of the highly saturated core is equal to $\dfrac{1}{d}$ square in., since the two cores are connected to the same external voltage $E$. The core working at low saturation produces a magnetization curve which is concave with respect to the $B$ axis whereas the highly saturated core produces a curve convex to the $B$ axis. If, now, the weight, $W$, is chosen large, then the character of the resulting $B_o - i$ curve will be determined by the current $i_1$, whereas, for a very small value of $W$, $i_o$ will be the controlling current. In between these two extreme cases, however, there will be a condition which will tend to average the two effects and a curve with a much larger radius of curvature and closer adherence to proportionality can be obtained.

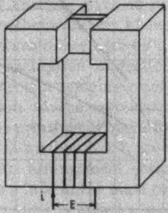


FIG. 3A—TWO-ELEMENT CORE

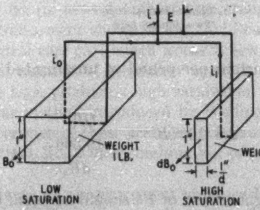


FIG. 3B—EQUIVALENT DIAGRAM FOR TWO-ELEMENT CORE

Fig. 2 shows the result of such an addition, $i_o$ and $i_1$ being given as functions of $B$ by equations (2) and (4) respectively, the resulting current approximating very closely the straight line $cB$. It is seen that in the neighborhood of point $C$ perfect proportionality is obtained since the tangent to $i_o + i_1$ at the point $C$ passes through the origin. Once proportionality is obtained for one point, it is likely to extend over a considerable range, and the mathematical formulation at one point thus will yield the condition for proportionality over such a range.

*Analytical Solution.* If the value of a function and its derivatives are known for a given point, then this function can be approximated by a potential series in the neighborhood of this point according to Taylor's theorem:

$$f(x_o + h) = f(x_o) + \frac{hf'(X_o)}{1!} + \frac{h^2f''(x_o)}{2!} + \ldots$$

In the following, a sufficient approximation is obtained by using the first two members only. The total magnetizing current per pound of unsaturated core is represented by

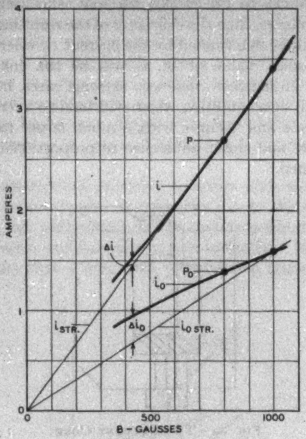


FIG. 4—MAGNETIZING CURRENT

$i_o$ Single-element core
$i$ Two-element core

$$i_o + i_1 = f(B) = 2.5\ 10^{-2}\, B^{0.6} + \frac{10W}{\dfrac{19{,}300}{dB_o} - 1} \qquad (5)$$

and in the neighborhood of *Bo* should be equal to *cBo*. The comparison of the coefficients of the Taylor series of these two functions furnishes the following equations.

$$2.5\ 10^{-2}\, B_o^{0.6} + 10W \frac{Bo}{\dfrac{19{,}300}{d} - B_o} = cB_o \qquad (6)$$

$$1.5\ 10^{-2}\, B_o^{-0.4} + 10W \frac{\dfrac{19{,}300}{d}}{\left(\dfrac{19{,}300}{d} - B_o\right)^2} = c \qquad (7)$$

These are the fundamental equations, by which *Bo*, *d*, *W* and *c* are connected.

*Example No. 1.* The effectiveness of this method is best illustrated by a practical example. In Fig. 4, $i_o$ represents the magnetizing current of a 1 lb. unit core working over a range from 400 to 1,000 gauss. The additional saturated core is selected to give proportionality for the point *P*, corresponding to $Bo = 800$ gauss, with its respective induction of $B_1 = 6{,}000$ gauss; *d* is, therefore, equal to 7.5 giving a weight $W = 0.28$ lb. and a coefficient $c = 0.0033$; *i* represents the total current, the straight line represented by *cB* is tangent to the curve at 800 gauss. To more easily verify the improvement obtained, a straight line $i_{oStr}$ is drawn through the 1,000 gauss point of $i_o$ and the difference $\Delta i_o$ between $i_o$ and $i_{oStr}$ calculated. In the same manner $\Delta i$ referring to a straight line through the 1,000 gauss point of the *i* curve, is computed. In Fig. 5, the curves corresponding to $\dfrac{\Delta i_o}{i_{oStr}}$ and $\dfrac{\Delta i}{i_{oStr}}$ are shown, the reduction of the value $\dfrac{\Delta i_o}{i_{oStr}}$ to $\dfrac{\Delta i}{i_{oStr}}$ is a direct measure of the decrease in the phase angle error for a purely ohmic burden, which can be obtained in a current transformer by the insertion of a highly saturated section into the main core.

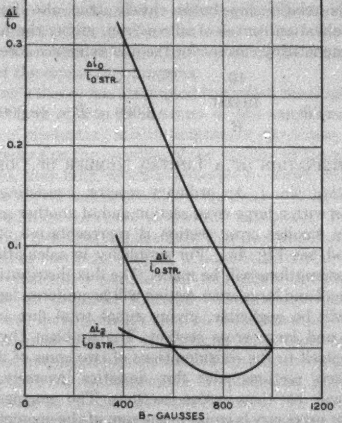


FIG. 5 $\dfrac{\Delta i}{i_{oStr}}$ FOR VARIOUS CORE COMBINATIONS

*Method No. 2.* In the previous two methods the ratio of the flux densities in the various cores was kept constant. In the following, two cores with a constant ratio of magnetizing ampere-turns will be considered. This condition can be obtained by putting the windings of the two cores in series, see Fig. 6A. The 1 lb. unit core working at the low flux density *Bo* is wound with one single turn, the other core working at high saturation $B_1$ is assumed to have the same length as the unit core, its cross section is equal to $A$ sq. in. and it is wound with $N$ turns. In this arrangement it is the relation between the applied voltage $E$ and the current $i_2$ which is of primary interest rather than the flux densities $Bo$ and $B_1$. Since the voltage $E$ is directly proportional to the sum of the flux linkages denoted by $\Sigma\Phi_k N_k$ proportionality between these and the current $i_2$ will be formulated.

$$\Sigma\Phi_k N_k = B_o + N \,.\, A \,.\, B_1$$

solving equation (2) for $Bo$ and (4) for $B_1$,

$$\Sigma\Phi_k N_k = 4.56 \ 10^2 \, i_2^{1\cdot 66} + 19{,}300 \, AN^2 \frac{i_2}{10 + Ni_2} \qquad (8)$$

and the conditions for proportionality at a point $i_2$

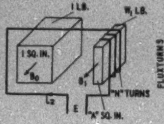
$$4.56 \ 10^2 \, i_2^{1\cdot 66} + \frac{19{,}300 \, AN^2 i_2}{10 + Ni_2} = ci_2 \qquad (9)$$

$$7.6 \ 10^2 \, i_2^{0\cdot 66} + \frac{193{,}000 \ AN^2}{(10 + Ni_2)^2} = c \qquad (10)$$

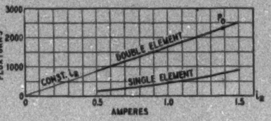
*Example No. 2.* To make a direct comparison with example No. 1 possible, the current $i_2$ and the number of turns $N$ for the point of proportionality $Po$ will be selected to result in $Bo = 800$ and $B_1 = 6{,}000$, giving

$$i_2 = 1.38 \text{ amperes}$$
$$N = 3.3$$

The fact that $N$ is a fractional number does not restrict the generality of the calculation. (9) and (10) give $A = 0.076$ sq. in. which number is also equal to the weight of the core in lb. Fig. 6B illustrates the resulting current-flux turn curve. Although proportionality is formulated for the point $Po$, the resultant curve is distinguished by its small deviation from the constant $i_2$ curve over its entire range. This method thus presents a powerful means for producing proportional characteristics. The values $\frac{\Delta i_2}{i_{oStr}}$ are plotted in Fig. 5.



A



B

FIG. 6A—CORE COMBINATION WITH LINEAR FLUX LINKAGE—MAGNETIZING CURRENT RELATION

FIG. 6B—FLUX LINKAGE—CURRENT RELATION FOR SINGLE AND TWO ELEMENT-CORE

The flux linkage value 2,675 in this example is chosen to coincide with $Bo = 1{,}000$ gauss of the previous example. This curve $\frac{\Delta i_2}{i_{oStr}}$ which is representative of the phase angle variation over the range, shows a great reduction compared to the original $\frac{\Delta i_o}{i_{oStr}}$ curve. From 600 to 1,000 gauss, the variation is practically zero, for the 400 gauss point it is reduced to 5 per cent of the corresponding $\frac{\Delta i_o}{i_{oStr}}$ value. It is also important to notice that for identical flux densities in the 1 lb. unit core, the addition of an exceedingly small saturated core increases by many times the number of flux linkages. The apparent permeability of the combination when referred to the low density core is thus increased accordingly.

## DISCUSSION OF AVAILABLE TRANSFORMER ERROR CORRECTING METHODS

The preceding analysis gives an explanation of certain correcting methods already known. Pfiffner[7] interrupts the main transformer core by a slot producing a portion at high saturation at section $X$, Fig. 7A. In addition he connects a separate reactor core $Y$ of uniform cross section to the secondary winding of the transformer. The principle of operation of this arrangement is identical to method No. 1, previously mentioned in this paper. An arrangement proposed by Wilson, Fig. 7B, provides a hole in the main core through which the secondary winding is linked a sufficient number of times to produce high saturation in the portion embraced.[8] The A.E.G.[9] (Allgemeine Elektrizitats Gesellschaft) on its newest high-voltage transformer uses a core arrangement shown in Fig. 7C. Besides embracing the central core part which works at low saturation, an unequal number of secondary turns is wound on the outside legs, producing high saturation. Fig. 7D shows a similar method introduced by Wellings and Mayo.[10] The operation of these arrangements is easily explained by method No. 2 or a combination of methods Nos. 1 and 2.

However, the improvement obtained by any of these methods is limited, according to published results, hardly exceeding a reduction of the errors to more than 50 per cent. An application of any of the above methods to bushing type current transformers for metering purposes would thus not be practical, since there, a reduction of the errors to one per cent or less is required.

## INFINITE NUMBER OF CORES

In the foregoing analysis, the magnetization curves resulting from the combination of a finite number of cores, have been investigated. Proportionality has been improved but not completely accomplished. Complete proportionality, however, can be obtained if an infinite number of cores is chosen, in analogy with the production of nature's magnetization curves, each infinitesimal core working at a different flux density. Whereas, in the previous calculation only flux densities were considered which were given by simple analytical formulas, cores working at any part of the magnetization curve are permissible, to produce a greater functional variety.

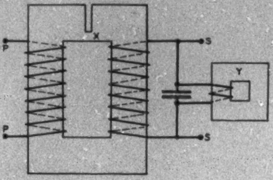


FIG. 7A—IMPROVED TRANSFORMER
Pfiffner

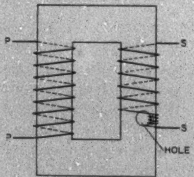


FIG. 7B—IMPROVED TRANSFORMER
Wilson

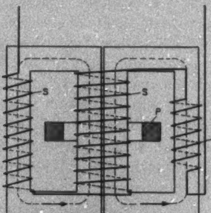


FIG. 7C—IMPROVED TRANSFORMER
A.E.G. (Allgemeine Elektrizitats Gesellschaft)

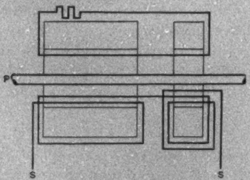


FIG. 7D—IMPROVED TRANSFORMER
Wellings and Mayo

A core of wedge shape such as represented in solid lines, Fig. 8, can be expected to fulfil the requirements. For simplicity it is assumed that the entire flux *Bo* which enters on the *x* axis is forced to $x = L$ without leakage and with equal distribution over each cross section. If the reactive voltamperes are represented by *RVA*/lb. $= f(B)$, the specific gravity denoted *s*, it follows

$$dW = 2ydxs$$

$$RVA = 2s \int_0^L yf\left(\frac{B_o}{y}\right) dx$$

and since proportionality between the magnetizing current and the flux is equivalent to a proportionality between *RVA* and $Bo^2$

$$cB_o^2 = \int_0^L yf\left(\frac{B_o}{y}\right) dx \qquad (11)$$

The solutions of this equation determine the various possible shapes of the wedge $f(xy) = o$. Since *RVA* per lb. $= f(B)$ is not known analytically over its entire range, a general solution is not possible and even if it were known, great difficulties would confront an attempt at such a solution, the determination of $f(xy) = o$ to give a certain $B - i$ relation is best accomplished by test.

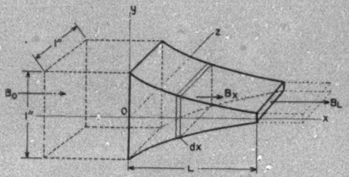


FIG. 8—CORE SHAPE PRODUCING REQUIRED FLUX—MAGNETIZING CURRENT RELATION

For this purpose a reactor was built whose otherwise uniform cross section was interrupted by a portion of varying cross section; to be able easily to vary $f(xy)$, laminations of ordinary transformer iron properly staggered are used.*

## THE ZERO ERROR CURRENT TRANSFORMER[11]

*Practical Construction.* All the necessary requirements for a zero error transformer being available, the most practical and economical construction has to be determined. This applies particularly to the location of the highly saturated portion; it has been previously stated that its weight must be very small to produce proportionality over the entire operating range, and means for easy initial adjustment should be available. The interruption of a core of a weight of several hundred pounds by one or a few laminations as shown in Fig. 7A, which in addition have to be properly staggered, is not mechanically feasible. Slight forces might change the adjustment and produce excessive errors. The arrangement Fig. 7B has similar disadvantages, provides poor means for adjustments and complicates the wiring and insulation of the secondary winding.

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*It was found that permeabilities constant within one-half of one per cent can easily be obtained over a flux density range from $B_o$ to $10B_o$.

If the reactor *Y* in Fig. 7A is provided with parts working at different degrees of high saturation, it will be capable of producing proportionality without interrupting the main core by a slot, which provided high saturation at *X*. The reactor will have to be provided with a portion working at low flux density, bringing the flux to the constricted section.

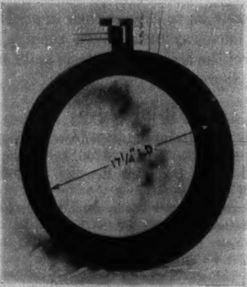

Fig. 9—270-Lb. Bushing Type Transformer Combined with Its Compensating Reactor

The advantages of this construction are apparent, since a small reactor of a weight of a few pounds in addition to a resistance or a capacitance is all that is required to transform any ordinary wound or bushing type current transformer into a zero error transformer. Adjustment of the laminations can be accomplished with ease. The reactor can be mounted directly on the transformer, or placed in any convenient location remotely from it, a feature which is particularly valuable for bushing type current transformers. Fig. 9 shows the combination of an actual bushing type current transformer core 17¼ in. inside diameter, 21¾ in. outside diameter, 7 in. high weighing 270 lb., and its compensating reactor. Its extremely small proportion is clearly visible.

All bushing type current transformers with low ratios are sensitive to a change in the secondary burden. There seems to be no simple means for the elimination of this sensitivity, since it is inversely proportional to the square of the number of secondary turns. Due to the fact that high accuracy can be obtained for very high secondary burdens, for instance, 50 volt amperes and over, an entirely new possibility presents itself.

The great disadvantage of all improved bushing type transformers is not the necessity of their requiring a laboratory calibration with the instruments to be connected, but the extremely low limit of the secondary burden to produce metering accuracy.

Frequent changes in the secondary burdens are made in certain specific cases, but can be considered the exception; the essential feature, however, is the possibility of making the transformer applicable for use over a great range of secondary burden possibly up to 50 volt amperes. This can be accomplished by the addition of a compensating burden, consisting of subdivided resistances and reactances.

The transformer is calibrated for a definite total burden of 50 voltamperes, 50 per cent power factor. In the case of an external burden of 20 voltamperes, 50 per cent power factor, resistances and reactances of the compensating burden have to furnish the missing 30 voltamperes, 50 per cent power factor.

For the purpose of verifying the calculated characteristics the performance of a specific transformer was determined. To keep the investigation in the range of highest voltages and the most frequent currents, the transformer shown in Fig. 9, arranged for 400/5 and 200/5 ratio was investigated.

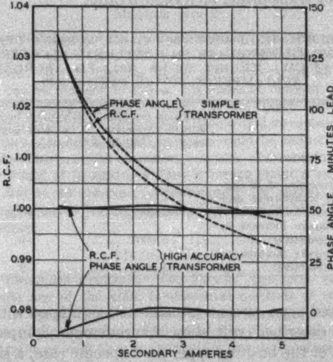

Fig. 10—Bushing Type Current Transformer 400-5, 60 Cycles

Internal diameter 17¼ in. (43.8 cm.); weight 270 lb. (122.5 kg.); external burden 50 voltamperes, 0.50 power factor

Most tests were performed by means of a test primary wound onto the bushing type transformer core, the turns being equal to the theoretical number of secondary turns, that is 80 turns for a 400/5 transformer.[12] This allows the use of comparative test equipment, such as a Silsbee set, without the necessity of a standard transformer or accounting for its errors. Testing is greatly simplified also, because a loading transformer is not necessary. Considered from the standpoint of field testing, the elimination of the standard and loading transformers will reduce the weight of equipment at least 80 per cent and save considerable time and risk. Results will be improved in accuracy by the elimination of the standard transformer since a fully distributed test winding has been found to be equivalent to a single central conductor by Knopp, and many others.[10,12,13] The equipment of bushing type current transformers with such a test primary is strongly recommended when they are to be used for metering purposes.

Fig. 10 gives ratio correction factor and phase angle characteristics for a 115-kv. bushing type current transformer with and without the transformer compensator, the high accuracy curve is plotted from points taken by an absolute (precision) test method. These data are given in tabular form in Table I.

TABLE I—TABULATION OF HIGH ACCURACY CHARACTERISTICS AS PLOTTED IN FIG. 10

| Secondary amperes | Ratio correction factor | Phase angle in minutes (+) indicates leading |
|---|---|---|
| 0.5 | 1.0006 | −11. |
| 1.0 | 1.0001 | − 7. |
| 2.0 | 1.0007 | 0. |
| 3.0 | 1.0004 | + 1. |
| 4.0 | 1.0000 | 0. |
| 5.0 | 0.9999 | + 1. |

Characteristic curves are insufficient to define the all around accuracy of a current transformer. Its sensitivity to burden and thermal changes is also necessary and Table II gives these values for the high accuracy transformer on its 400/5 ratio.

TABLE II—HIGH ACCURACY 115-KV. BUSHING TYPE CURRENT TRANSFORMER 400-5. INTERNAL DIAMETER 17¼ IN. (43.8 CM.), WEIGHT 270 LB. (122.5 KG.), BURDEN 50 VOLTAMPERES, POWER FACTOR 0.50

| Due to: | Maximum increment in ratio correction factor. (+) indicates increase | Maximum increment in phase angle in minutes. (+) indicates leading |
|---|---|---|
| Temperature rise of 10 deg. cent. of transformer and transformer compensator | +0.0001 | +1. |
| 1.0 voltampere increase in burden (resistive) | +0.0007 | +6. |
| 1.0 voltampere increase in burden (reactive) | +0.0013 | −3. |

Wound type current transformers equipped with the device described will show improvement comparable to that of the bushing type. In a specific case, a simple 69-kv. wound type, with a burden of 50 voltamperes and secondary current range of 0.5 to 5 amperes has a variation in error of 0.008 in ratio correction factor and 13 minutes of phase angle. This transformer under the same conditions can be improved in characteristics so that its maximum errors are within the accuracy of commercial test equipment; namely, 0.001 in ratio correction factor and 3 minutes of phase angle. Further improvement is possible but is not considered to be of commercial value.

### CONCLUSION

1. The improvements described have brought low ratio silicon-iron core bushing type transformers into a range of accurate performance sufficient for metering, approaching that of a watthour meter.

2. Although extra circuits and equipment are required, they are not on the transformer itself and are readily accessible.

3. The useful burden on the transformer may be large and changed to a considerable degree with no appreciable effects on the transformer calibration, providing proper adjustment is made in a burden compensator.

### ACKNOWLEDGMENT

The authors wish to express their appreciation of the advice and encouragement given them by Mr. Roy Wilkins and of the assistance in tests and computations by Mr. J. K. Siewertsen.

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## Discussion

**G. Camilli:** It appears to me that the characteristic curve $C$ shown in Fig. 1 is misleading, in that it does not represent the approved method of application of the two-stage principle. According to this curve, it looks as though phase angle of the Brooks' two-stage current transformer (curve $C$, Fig. 1) is worse than that obtained by the simple uncompensated current transformer.

I have no doubt that the authors have actually obtained their curve $C$ with the design and arrangement that they set up, but, apparently, their set up was not such as to produce the best results which the two-stage principle is capable of. The following presents data on a two-stage unit that is more representative:

*Modified Two-Stage Bushing Type Current Transformer for 132-Kv Bushing.* Dimensions of the main secondary core (silicon steel) were as follows:

Inside diameter = 18 in.
Outside diameter = 24½ in.
Height = 4 in.
Weight = 195 lb

The tertiary core had the same dimensions as the main core with the exception that its height was only 1½ in. This core was made of permalloy 0.014 in. in thickness and was formed by winding up strips which previously had been spot welded. The weight of this core was 59 lb.

The following tests were made at 100 amp, primary current. Total secondary burden 1.0 ohm at 0.69 power factor, plus 1 amp G.E. I-16 element. Tertiary burden 0.44 ohm at 1.0 power factor plus 1 amp G.E. I-16 element.

| % primary current | Ratio correction factor | Phase angle |
|---|---|---|
| 100 | 1.0010 | +15′ |
| 60 | 1.0018 | +12.5′ |
| 20 | 1.0018 | + 3.2′ |
| 10 | 0.9997 | − 5.8′ |

It might be pointed out that the above results were obtained with the current transformer under such unfavorable conditions as a primary current one-half of that used by the authors and a length of magnetic circuit 1.25 times as large. Favorable elements were somewhat larger cross section and apparently smaller burden.

This variance may make a comparison difficult, but they are irrelevant to the point I wish to make, namely, that excellent results may be obtained by a judicious design and application of the two-stage principle.

An important consideration in obtaining the utmost from the modified two-stage principle is to two-stage only the wattmeter current coil (excluding ammeters, relays and any other series impedance) and then to compensate only for the wattmeter current coil.

**A. C. Schwager and V. A. Treat:** Mr. Camilli has given an excellent example illustrating the high accuracy now available with high voltage bushing type transformers of low ratio. We regret that space limitations made it necessary to omit a more thorough discussion on the two-stage and modified two-stage principle, in which the corrective ability of these methods was more fully shown, and the favorable results for high ratios or low burdens have been pointed out. The reader is referred to the publication: "Der Fehlerlose Stromwandler," by A. C. Schwager, *Bulletin des Schweizerischen Elektrotechnischen Vereins*, No. 20, 1932 where most correcting methods known have been treated analytically; the calculations and data given below are based on the formulas developed in this publication.

From Mr. Camilli's discussion it appears as if the favorable results obtained by him were due entirely to the application of the modified two-stage principle; this viewpoint as well as the comparison with our 200/5 ratio transformer are misleading. In the following it will be shown that the improvement obtained by him is only to a small portion due to the two-stage principle, the larger portion being brought about by two additional methods of correction, distinctly different from the two-stage principle. To identify his transformer as two-stage transformer therefore remains a matter of designation only, the improvement over an ordinary silicon iron transformer has to be analyzed on the basis of additional methods. Both of these methods are well known and in general use; one, is the use of instruments with a normal full current rating of 1 ampere, and the other is the application of a high permeability nickel iron core material.

### METHOD NO. 1

*Instruments with 1 Ampere Full Current Rating.* It is well known that in outdoor metering installations using 5 ampere normal current, the resistance due to the leads from the transformers to the watthourmeter constitutes the largest part of the burden. Taking the data from Mr. Camilli's tertiary circuit it is seen that the leads at 5 amperes would absorb 0.44 × 25 = 11 watts, whereas the watthourmeter draws 1.3 va only. If the normal full load current is reduced to 1 ampere then these leads consume only 0.44 watt, the wattmeter still requiring 1.3 va. In the following calculations these 1.3 va will be assumed at 100 per cent power factor, the phase angles computed in this manner will be slightly larger than the actual ones and favoring Mr. Camilli's transformer in a comparison.

In the publication mentioned above the phase angle error of a transformer with a ratio of outside to inside diameter of 1.25 operated at a purely ohmic burden $r$ is given by:

$$tg\,\theta \simeq \theta = 1.77.10^{12}\,\frac{s\,\gamma_M D^{0.4}\,r^{0.6}}{H^{0.6}\,N^{1.6}\,I_2^{0.4}} \tag{1}$$

Where $s$ = specific gravity in lb/in.$^3$

$$\gamma_M = \frac{RVA/16}{B^{1.6}} = \left\{ \frac{4.3\ 10^{-7} \text{ for silicon iron}}{4.4\ 10^{-8} \text{ for nickel iron}} \right.$$

$D$ = inside diameter of core in inches
$H$ = height of core in inches
$N$ = number of secondary turns
$r$ = resistance of secondary burden in ohms
$I_2$ = secondary current in amperes.

In all the following discussions we assume $D = 15$ in., $H = 7$ in. An ordinary 100/5 amp silicon core transformer with a purely ohmic secondary burden of 12.3 watts (0.49 ohms) according to the above equation has an error of approximately 1,300 minutes (21 degree). Using a 100/1 amp transformer however, reduces the error to 400 minutes. The great improvement obtained for identical secondary resistance by the use of a 1 amp normal current current transformer is apparent.

### METHOD NO. 2

*Use of Nickel Iron Alloys as Core Material.* The value of high permeability nickel iron alloys as core material is generally recognized. By its use the phase angle errors for an ohmic burden can be reduced to 1/10th the value of those of the corresponding silicon core transformer. If the silicon core of the 100/1 amp transformer considered above would be replaced by a Ni-Fe core, the error of 400 minutes could be reduced to 40 minutes. The powerful corrective capacity of a combination of scheme I and II is apparent since it brings about a reduction from 1,300 to 40 minutes (approximately 32 times), leaving errors higher but of the same magnitude as given for Mr. Camilli's transformer.

### METHOD NO. 3

*The Two-Stage Principle.* The Brooks' two-stage principle represents one of the most fundamental methods of reducing errors. If the errors in the first stage are inherently small (for instance, of the magnitude of 60 minutes in phase angle or 1 per cent in ratio, or less), then the correction due to the second stage is considerable, a reduction of the errors by 5 to 10 times can be satisfactorily accomplished. The method is particularly useful for standard transformers. As soon as the errors in the first stage become excessive (of the order of several degrees in phase angle or several per cent in ratio) due to a large burden or a low transformer ratio, the corrective ability of the original two-stage and particularly that of the modified two-stage (due to the doubled burden) is rapidly lost as shown by curve $C$ of our Fig. 1 referred to by Mr. Camilli.

### COMBINATIONS OF METHODS 1, 2 AND 3

It is evident that the application of the two-stage principle to a Ni-Fe core would produce a radical improvement. Economical consideration however makes it advisable to restrict its application to the auxiliary core only. The use of these two principles alone however is not capable of producing the necessary accuracy. This fact is very definitely illustrated by test made by the A.E.G.[1] where a 200/5 A transformer at 15 va, 100 per cent power factor using the modified two-stage principle with auxiliary Ni-Fe core reduces phase angle errors only 5 times. The corrected transformer still shows an error in excess of 100 minutes at 10 per cent secondary current. In this way satisfactory results cannot be obtained.

The additional necessary improvement has to be brought about by another principle, which corresponds to our method 1, using 1 ampere normal full current. The proper combination of scheme 1, 2 and 3 is then sufficient to bring about the accuracy required and shown in tabular form by Mr. Camilli.

### METHOD NO. 4

*Use of Constant Permeability Core.* The method of shaping magnetization curves described by us gives an additional independent means of reducing the errors. Since the reduction due to the apparent constant permeability of the main and reactor core combination is approximately 100 times in ratio and phase angle, the errors of the ordinary 100/5 amp silicon core transformer are reduced from 1,300 minutes to approximately 13 minutes. This method is therefore capable of producing in one step the improvement that a combination of 1, 2 and 3 is able to yield. Standard instruments can be used, the use of the expensive Ni-Fe alloy core is eliminated and there are no complications due to the splitting up of the core in sections to allow the use of the two-stage principle. The advantages in initial cost and simplicity in operation are apparent since this method, in addition to the ordinary core and winding, requires but a small reactor of approximately one pound weight and a resistance or a capacitance.

### COMBINATION OF METHOD NO. 4 WITH METHODS 1, 2 AND 3

Whereas Mr. Camilli's transformer has already used the first three mentioned correcting methods, these can now be applied to the constant permeability transformer. If the 100/5 transformer considered in Method No. 4 is changed into a 100/1 transformer, the resulting phase angle error will not be in excess of 5 minutes, a result which is easily verified by equation (1). This transformer makes possible a direct comparison with the errors listed for Mr. Camilli's 132-kv transformers. Since the phase angle error in his case is 15 minutes it is evident that our 100/1 transformer with a maximum error of 5 ft is greatly superior to Mr. Camilli's transformer. This comparison is justified since Mr. Camilli's transformer also operates at 1 amp normal full current; his comparison with our 200/5 ratio transformer is therefore misleading.

If the core of our 100/1 transformer is replaced by a Ni-Fe core a 25/1 transformer with an error not exceeding 5 ft results. Without the use of the constant permeability principle such accuracies at low ratios cannot be obtained by any other correcting method, and it therefore opens an entirely new field of application for bushing type transformers. Still lower ratios could be obtained by the additional application of the two-stage principle, although the demand for them is less pronounced.

The two-stage principle however is capable of producing improvements on low ratio transformers which are more important than a further reduction in ratio, and in the future promise it a wide field of application. All low ratio current transformers, (such as our 25/1 or Mr. Camilli's 100/1) are sensitive to burden changes. These transformers have to be given an accurate calibration with the instruments and leads with which they are used. Temperature changes in the resistance of the watthourmeters can cause a sufficient variation in burden to slightly impair the otherwise high accuracy. With the original Brooks' two-stage principle goes the ability to correct automatically the two-dimensional multiplicity of current—as well as burden changes. This latter feature makes it possible to produce transformers practically insensitive to such unavoidable burden changes and it can be applied with success on the lowest ratio transformers; the necessary use of two-stage meters should not prevent its general application to such cases. The modified two-stage principle, using single element instruments unfortunately is not capable of correcting the burden variation, a fact which is easily overlooked.

### WOUND TYPE TRANSFORMERS

In spite of the progress made in the design of accurate bushing type current transformers, the wound type transformer will maintain a limited field of application. It will fill the gap for the lowest ratios, such as 5/5 to 100/5, and will also be used in all cases where insensitivity to fairly large burden variation is imperative, such as due to changes in the number of instruments connected. Such transformers, particularly for highest voltages, due to the large amount of iron used, still show relatively large inherent errors, such as 30 to 60 minutes in phase angle and 0.25 to 0.5 per cent in ratio. Such errors are excessive in all cases where large blocks of power are measured, as in the case of system interconnections.

These errors can be reduced to less than 10 minutes in phase angle and 0.1 per cent in ratio by any of the four correcting methods described. Whereas 1, 2 and 3 would require special instruments, expensive core material or complicated core construction, respectively, the Method No. 4 illustrated by the authors brings about the required correction at practically no additional cost or complication and seems advisable in all cases. It is even possible to reduce the errors of any installed wound transformers to practically zero by the simple addition of the small reactor and a resistance or capacitance.

In conclusion we hope that this discussion has clearly analyzed the improvements obtained by Mr. Camilli and given a more justified comparison between the various methods of improvements of current transformers.

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[1] J. Goldstein, "Die neveste Entwicklung im Stromwanderbau," *E.T.Z.*, Volume 18, 1932, p. 429.

# Corona Loss Measurements for the Design of Transmission Lines to Operate at Voltages Between 220 Kv. and 330 Kv.

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Associate, A.I.E.E. Associate, A.I.E.E.

***Synopsis.**—Corona loss measurements were obtained on conductors of three different diameters; namely, 1.125 in., 1.49 in. and 2.0 in. Voltages up to 600-kv. line voltage were used in these measurements. Various surface conditions of the 1.125-in. cable were studied. These measurements include tests on the new cable as received, the cable as washed, scratch brushed, buffed and dragged. The aging of the dragged cable was observed for seven months. Data were obtained on the daily variation of loss. The effects of configuration and transposition were studied on No. 2 wire. A description of the modifications in the high-voltage wattmeter for these high-voltage measurements is reported.*

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### INTRODUCTION

DURING the summer and fall of 1931, measurements at the Harris J. Ryan Laboratory, Stanford University, extended the range of corona loss data for conductor sizes beyond those investigated during 1930, the results of which were presented in an A.I.E.E. paper.[1] This investigation was made possible by the Department of Water and Power, City of Los Angeles, and the results of this investigation are being used in the economic study of the transmission of Boulder Canyon power to the City of Los Angeles.

The three conductor specimens studied in these tests were a 1.125-in. hollow copper cable, a 1.49-in. hollow copper cable and a 2.0-in. hollow aluminum cable. See appendix I. The losses were measured on a three-phase line 700 ft. long. Voltages as high as 600 kv. between lines were used.

### GENERAL DESCRIPTION OF LAYOUT

For the comparison of losses the different conductor specimens were always mounted in a horizontal configuration with a clearance to ground of 30 ft. and a sag of 16 ft. The spacing was such that the ratio of $S/r$ was practically the same for all the tests except that of the 2.0-in. conductor in which for good clearance the physical dimensions limited the spacing to 30 ft. For the method of supporting conductors, see reference 1.

Certain variations of the loss due to the surface condition of the conductor had been found by previous test, but it was desired to carry on such tests over a wider range of conditions, such as scratch brushing and polishing the conductor, which gave an ideal surface; and dragging the conductor, which left it more nearly the same as found in actual practise.

Since so much depends on the surface condition of the conductor, considerable care was taken in the handling of the specimens. For example, the new 1.49-in. cable that was shipped from the factory on one reel was rewound onto three smaller reels. As it was rewound, it was carefully taped with heavy wrapping paper. In the process of erection the reels were mounted on a truck in a frame, and the cable was paid out from the truck along on the dry ground directly under the insulator supports. The clamps were put on, and as the cable left the ground the paper was removed. This left the cable almost in the identical condition it was when it left the factory. When the 1.125-in. cable was lowered for washing, scratch brushing or buffing, it was not allowed to touch the ground. This was accomplished by means of heavy wooden horses about 4 ft. high. These horses were placed from 50-ft. to 60-ft. apart. At the top of each horse was a wooden roller which allowed the conductors to move freely without being scratched and without danger of the horses being pulled over. To preserve the clean and polished surface of the 1.125-in. cable, it was also taped with heavy paper immediately after scratch brushing and buffing. This wrapping was not removed until the cable was being erected just before test.

The insulator strings used on the 1.125-in. cable were of 18 units, 10-in. diameter, and were shielded at the lower end with a Koontz type shield. The insulator strings for the 1.49-in. and the 2.0-in. cable were similar, but were shielded on each end by means of an aluminum ring radio shield. See Fig. 10. The diameter of the tube of which this ring was made was 2.5 in. and the large diameter of the ring was 22 inches.

The voltage was applied to the line by means of three 350-kv., 350-kva. transformers Y-connected on the high-voltage side, and delta-connected on the low-voltage, or 2,300-volt side. These transformers were energized from a 2,300-volt sine-wave alternator.

Fundamentally, there was no difference in the method of making these measurements from those reported in the former paper. Briefly, this measuring method involved the use of three single-phase, high-voltage wattmeters, each being connected directly between one

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[1] See Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

line and ground. Dynamometer type meters were used. The line was fed directly through the current coil of the meter, and the potential coil was connected directly between line and ground by means of a high-voltage, water resistor multiplier.

Certain modifications in the former measuring equipment were necessary in order that satisfactory tests be carried on with the larger conductors. One change was the mounting of the test specimen nearer the laboratory, thereby reducing the length of the shielded wattmeter lead from 450 ft. to 100 ft. This reduced the error caused by the capacitance between the lead and shield shunting the field coil of the wattmeter to a negligible value up to the highest voltage used. The description of the 350-kv. wattmeter multiplier is given below.

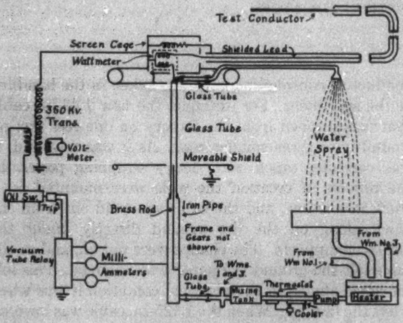

Fig. 1—Wattmeter Connections

## High-Voltage Wattmeter Multiplier

This multiplier consisted of a glass tube 0.4-in. inside diameter and 1/16-in. glass, mounted between two circular, iron mesh shields four feet in diameter. The lower shield was mounted on a movable frame work actuated by screws. The upper shield was supported by means of redwood sticks 1½ in. in diameter. These sticks were dried out in an oven at a temperature of approximately 110 deg. cent. until they showed no further decrease in weight. They were then placed in a bath of paraffin at this same temperature, the paraffin was allowed to cool until it began to solidify and then the sticks were removed having a thick coating of paraffin on the outside. When completely cooled, the excess paraffin was carefully removed. This gave a dry insulating support sealed against absorption of moisture. This support was better than Bakelite or similar insulation, because of its lower dielectric constant requiring less charging current; and at the same time, disturbing to a lesser degree, the field about the water resistor.

Mounted on the edge of the upper shield was a torus six inches in diameter which showed no signs of corona at 350 kv. Inside the glass tube was arranged a brass rod 1/8 in. in diameter. This rod was mounted in a water-tight cylinder below the lower shield in such a manner that it moved upward by means of a screw arrangement at the same rate as the lower shield. With such an arrangement, the shield and the brass rod moving together, the resistance of the multiplier could be changed uniformly and have correct shielding at all times. A schematic diagram of the equipment is given in Fig. 1 and the high-voltage multiplier is shown in Fig. 2. Distilled water was circulated through the glass tubes of the three multipliers by means of a pump, the water being discharged at the high-voltage end through a spray similar to the method used in previous measurements. By the use of the distilled water a multiplier of minimum length could be made, reducing the capacitance of the resistor to the shields and to ground to a minimum. For this reason, if the voltage distribution along the resistor did not conform exactly to the field between the shielding plates the error introduced by the charging current from the resistor would be extremely small because of the resistor dimensions. At 350 kv. and with 50 milliamperes of current there are 17.5 kw. of energy absorbed by the resistor. To prevent excessive rise in temperature the water flows through each resistor at the rate of 5 gallons per minute. This gives a temperature rise up the water column of 13 deg. cent. To reduce the error introduced by the change in resistance of the water due to increase in temperature, the water entering the resistor was maintained by means of thermostat control at a temperature of 40 deg. cent. At this temperature, the energy dissipated due to evaporation in the spray is approximately 5 kw.; so that at low voltages the energy absorbed by the multiplier was less than that dissipated in the spray. In order to maintain this 40 deg. cent. temperature it was necessary to heat the water before it entered the multiplier. At the higher voltages the energy absorbed by the multiplier was greater than that dissipated by the spray. Under these conditions it was necessary to

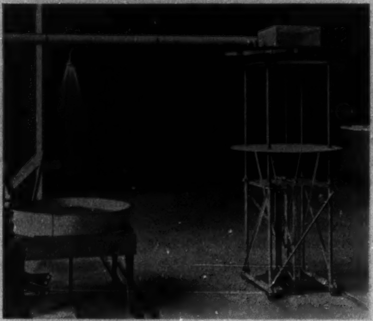

Fig. 2—High-Voltage Wattmeter Multiplier

cool the water. This was done by means of a water cooling coil.

As the water is circulated through the system it picks up certain impurities and in time the resistance lowers sufficiently to necessitate some adjustment. This adjustment of the resistance of the water was accomplished by means of an arrangement, the principle of which was observed before the wattmeter was built. By passing the water between plates of aluminum and carbon with d-c. potential of 125 volts between the plates, the aluminum being positive, the resistance of the water was found to increase considerably and in some cases it was possible to increase it as much as five times its original value.

The wattmeter instruments were protected by means of low-voltage safety gaps across their coils and also by a special vacuum tube relay in the ground end of the multiplier.

### MEASUREMENTS

At the beginning of this test the engineers on the project said that it would be their aim to keep the corona loss a minimum within reasonable limits of conductor cost. A loss value of ½ kw. per mile was suggested to be kept in mind, for test purposes. At a voltage of 275 kv. this means a power factor of the test specimen of 0.1 per cent. Such a condition is extremely exacting when it comes to measurements at such high voltages. It was necessary to check carefully all possible sources of error in the measuring equipment and approximate their magnitudes. Such sources included the shielding of the water resistor multiplier, the capacitance between the wattmeter lead and its shield, the wattmeter itself, and the measurement of the voltage.

One of the meters used in the test was calibrated at the Department of Water and Power Testing Laboratory. The other meters were calibrated at the Ryan Laboratory using this meter as a standard. There were no standards conveniently available for use at these extremely low power factors; so a further check by an absolute method was devised. Two similar wattmeters were connected in a circuit so that the mutual inductance of their coils balanced. By means of a condenser in the current coil circuit and a variable inductance in the potential circuit, the current in the potential coil was shifted until it was exactly at right angles to the current through the current coil. This was indicated by zero reading on both of the wattmeters for both direct and reversed readings. The magnitudes of the currents were made of the same order as those on corona tests and were measured by milliammeters. The resistance, inductance and capacitance of the circuit were known. By inserting a small known resistance in the current coil circuit, the phase angle of the current was shifted a small amount from the 90 deg. position. The amount of this shift was computed from the constants of the circuit. For power factors of the order of 0.1 per cent the calibration of the meters was comparable to that at higher power factors, as determined by comparison with standards.

The determination of the line voltage was made from the voltmeter coil of one of the transformers. With the line connected this was carefully checked with the 50-cm. sphere gap, and found to be slightly in error. A calibration curve was taken for the voltmeter coil and the voltage correction was made in all of the computations. A power circuit, harmonic analyzer measurement of the voltmeter coil voltage and also of the current through the high-voltage wattmeter multiplier showed the voltage wave to be very nearly sinusoidal. For example, with the 2.0-in. cable operating at 450-kv. line voltage, the highest harmonic was the fifth, its value being 0.9 per cent. The next highest harmonic was the third with a value of 0.3 per cent. None of the other harmonics were in excess of 0.1 per cent. The magnitude of the harmonics increased slightly as the corona loss was increased by higher voltages.

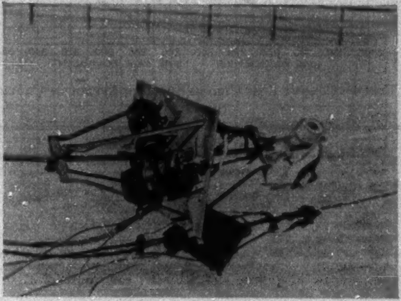

FIG. 3—ASSEMBLY OF BUFFING MOTORS

Measurements of air temperature and humidity were similar to those of previous tests, thermometers being placed in the shade out-of-doors and in the direct air stream from a small fan. However, one addition was made to this equipment; namely, a short specimen of cable with a thermometer mounted on the inside in such a manner that it could be removed and the temperature of the cable read. This cable was always mounted in the sun about six feet above the ground, and the assumption was made that the temperature as recorded here was the same as that of the test specimen.

### DISCUSSION OF RESULTS

During the tests described in this paper, variations in loss were observed during the day that are far in excess of that which could be accounted for by the variation in $\delta$, the air density factor. Further, data now being collected, yet not sufficiently studied to be presented at this time, indicate that the value of $\delta$ should be calculated from the conductor temperature rather than the air temperature, and that the variation of $E_0$ with $\delta$ is not a direct proportion, as previously assumed, but is some other function of the air density factor.

As the volume of data available on corona loss is increased the difficulty of obtaining a formula to fit all of the curves for the conditions involved is more evident. Any one calculating corona loss on lines realizes that the economic range for operating lines is with the conductors of a diameter so that the corona loss is below 10 kw. per mile, and, in many cases, the economic conductor size is such as to give a corona loss of less than 1 kw. per mile. Since these low values of loss are the most needed and since it is in this range that the present existing formulas[2,3] and test results show the greatest deviation, the data given in this paper are presented as recorded with voltage and meter corrections only; no correction for air density having been made.

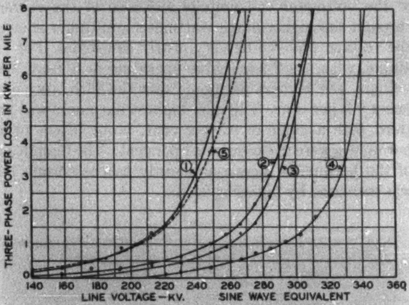

Fig. 4—Corona Loss Curves Showing Effect of Cable Surface

1.125-in. cable—22-ft. horizontal spacing

| Curve No. | Barometer in. hg. | Temperature—deg. fahr.<br>Dry bulb | <br>Wet bulb | <br>Cable | Date | Surface condition |
|---|---|---|---|---|---|---|
| 1 | 29.79 | 77 | 66 | ... | 8-28-31 | New |
| 2 | 29.84 | 77 | 65 | ... | 9- 3-31 | Washed |
| 3 | 29.92 | 69 | 59 | 71 | 9-28-31 | Scratch brushed |
| 4 | 29.84 | 72 | 55 | 80 | 10- 3-31 | Buffed |
| 5 | 29.78 | 64.5 | 57 | 66° | 10-13-31 | Dragged |

*Study of Surface Conditions.* As had been found in the previous measurements at the Ryan Laboratory,[1,4] the die grease or other foreign matter that exists on the cable as it is received from the manufacturers causes a very material increase in the corona loss. New cables, washed with gasoline and further washed with a soap solution and thoroughly rinsed with water showed a substantial decrease in loss from that found on the new cable unwashed. All of the cables tested were treated in this manner; namely, tested as received from the factory, or as nearly so as possible, and then thoroughly washed and again tested. In addition to these two surface conditions, the 1.125-in. cable was tested after three other treatments of the surface, namely, scratch brushed, buffed and dragged. The curves for the various surface conditions of the 1.125-in. cable are given in Fig. 4.

Curve No. 1 is the loss as found on the cable when it was first erected. This cable had been stored at the laboratory for three years. Curve No. 2 gives the loss as obtained after the washing treatment. The explanation of the physical change resulting in the very unusual electrical change cannot be given. It has been found to exist wherever new cables have been tested and then washed, and is further evidenced by the very excessive noise on new lines that gradually decreases with aging of the lines.

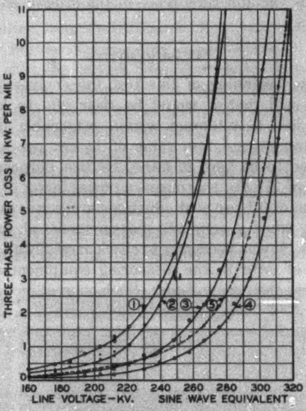

Fig. 5—Corona Loss Curves Showing Aging of Dragged Cable

1.125-in. cable—22-ft. horizontal spacing

| Curve No. | Barometer in. hg. | Temperature deg. fahr.<br>Dry bulb | <br>Wet bulb | <br>Cable | Date | Surface condition |
|---|---|---|---|---|---|---|
| 1 | 29.78 | 64.5 | 57 | 66 | 10-13-31 | Dragged |
| 2 | 29.87 | 68 | 58 | 78 | 10-14-31 | Dragged |
| 3 | 30.14 | 60 | 56 | 78 | 12- 4-31 | Dragged |
| 4 | 30.17 | 60 | 50 | 68 | 1- 6-32 | Dragged |
| 5 | 29.84 | 77 | 65 | | 9- 3-31 | Washed |

The curve No. 3 was obtained on the 1.125-in. cable after it had been completely polished with steel scratch brushed. This polishing was done by mounting the brushes on one-half horsepower motors which were carried along on the conductor by a frame supported on rubber-tired castors. See Fig. 3. This treatment produced a satin finish, removing all oxides and giving an absolutely clean cable. This surface appeared, when examined under a magnifier, as though it had been hammered with extremely minute hammers. These minute depressions were uniform over the complete cable and were not nearly so deep as the die marks found on many acceptable cables. This treatment, as seen from the curve, produced a very slight decrease in the corona loss.

Curve No. 4 was obtained on the 1.125-in. cable after it had been buffed with cotton buffing wheels and nickel rouge as an abrasive. This treatment produced an extremely high polish on the cable; so that it could be classed as having a roughness factor of unity other than that imposed by the stranding. As can be seen from the curves, this buffed cable had an extremely low loss. Unfortunately, this was not a permanent condition and the aging of this surface is discussed in a later paragraph.

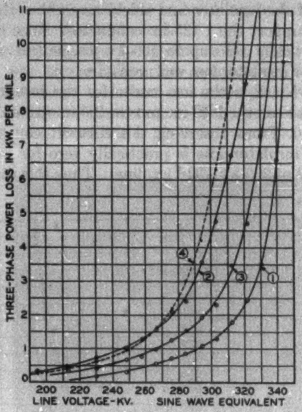

Fig. 6—Corona Loss Curves Showing Aging of Buffed Cable

1.125-in. cable—22-ft. horizontal spacing

| Curve No. | Barometer in. hg. | Temperature deg. fahr. Dry bulb | Wet bulb | Cable | Date | Surface condition |
|---|---|---|---|---|---|---|
| 1 | 29.84 | 72 | 55 | 80 | 10- 3-31 | Buffed |
| 2 | 29.95 | 68 | 58.5 | 80 | 10- 5-31 | Buffed |
| 3 | 30.05 | 69 | 59 | 79 | 10-12-31 | Buffed |
| 4 | 29.84 | 77 | 65 | | 9- 3-31 | Washed |

To more nearly simulate the conditions as encountered in field erection, the cable was dragged for one-half mile in the fine crushed rock on a road shoulder. This produced a decided roughening of the surface and carried with it considerable dirt from the road. The cable as erected after this treatment gave a loss as shown by curve No. 5. It was rather surprising to see that this curve fell below the loss curve for the same cable as received from the factory. However, it should be remembered that the grease, die compound or other foreign matter had been completely removed from the conductor before it was dragged; so that this condition may be better than that which would result from a new cable that was dragged in erection. This rough surface also aged rapidly and is discussed in the following paragraph.

*Aging of Surfaces.* In order to have some definite information as to the aging of dragged cables, the 1.125-in. cable was allowed to remain in place for seven months. During this time appreciable aging occurred as is shown in Fig. 5. The aging was uniformly progressive as shown by curves No. 1, 2, 3 and 4, decreasing the loss with time. Curve No. 1 was taken immediately after the cable was dragged. Curve No. 4 shows that the loss has decreased until it is less than that for the washed cable, which is given by the dotted curve, No. 5. A further test taken at the end of the seven months, shows that the loss is practically unchanged. This decrease of corona loss due to aging of the conductor is extremely gratifying and helpful as it eliminates the need for purchasing excess copper or expensive erecting precautions to eliminate the loss resulting from slight roughening.

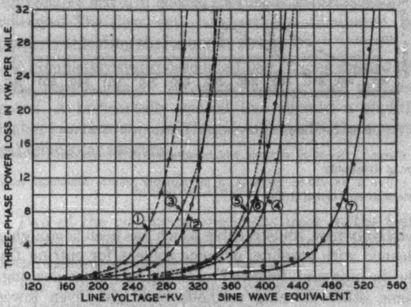

Fig. 7—Corona Loss Curves Showing Variation of Loss with Diameter

| Curve No. | Cable diameter in in. | Barometer in hg. | Temperatures deg. fahr Dry bulb | Wet bulb | Cable | Date | Horiz. spacing in ft. | Surface condition |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.125 | 29.79 | 77 | 66 | | 8-28-31 | 22 | New |
| 2 | 1.125 | 29.84 | 77 | 65 | | 9- 3-31 | 22 | Washed |
| 3 | 1.49 | 30.01 | 68 | 58 | 76 | 10-23-31 | 30 | New |
| 4 | 1.49 | 30.05 | 71 | 53 | 80 | 10-27-31 | 30 | Washed |
| 5 | 1.49 | 29.85 | 80 | 59 | 82 | 10-29-31 | 22 | Washed |
| 6 | 2.0 | 29.93 | 82 | 61 | 93 | 11- 6-31 | 30 | New |
| 7 | 2.0 | 30.05 | 66 | 48 | 80 | 11-12-31 | 30 | Washed |

The aging of the buffed cable was not so uniform in progression as that of the dragged cable. By reference to Fig. 6 it can be seen that the lowest loss as found on the buffed cable is that of curve No. 1, obtained on the day the buffing was completed. Two days later the loss was much higher, as shown by curve No. 2. This curve approaches the loss value as obtained on the washed cable, as given by the dotted curve, No. 4. Nine days after the buffing as shown by curve 3, the loss had decreased to a lower value again, but not so low as that obtained immediately after buffing. The only explanation that can be given for this irregular behavior of the buffed cable is that the surface was more perfect than could be obtained in open air.

From the observations of the various conditions as they effect corona loss, it can be said that the reliable surface to use for the comparison of cables is that of a relatively new, unused cable which has been thoroughly cleaned with gasoline, or some solvent for cutting the the die lubricant, followed by a soap and water cleaning. Some other cleaning methods may give even lower corona loss, but all cables to be compared should be cleaned in the same manner. For this reason the comparison of the different sizes is made on the basis of the washed cable tests.

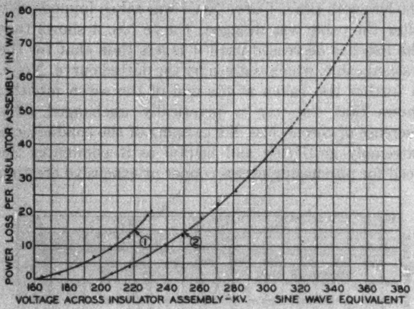

Fig. 8—Loss Curves on Insulator Strings

Curve 1. 18—10-in. sections, 5 in. hanging length. Koontz shield on lower end of string only

Curve 2. 18—10-in. sections, 5 in. hanging length. Aluminum radio shields at each end of string

*Comparison of Size of Cable.* The curves of Fig. 7 show the loss values as obtained on the 1.125-in., 1.49-in. and the 2.0-in. cables. It can be seen from the curves for the washed cables, Nos. 2, 4, 5 and 7 that the voltage shift for the same power loss is practically proportional to the part of $E_0$ which is affected by dimensions; namely, $r \log S/r$, where $E_0$ is the disruptive voltage, $r$, the radius of the conductor and $S$, the spacing. The washing of the 1.125-in. cable shifted the loss so as to allow it to operate with the same loss, 40 kv. higher than the new unwashed cable. By washing the 1.49-in. cable it was shifted approximately 100 kv.; and for the same loss the 2.0-in. cable was shifted approximately 110 kv. higher by washing.

Curve No. 5 of Fig. 7 is the loss curve on the 1.49-in. cable with 22-ft. spacing, and was obtained after the cable was washed and after the loss measurements were obtained with the 30-ft. spacing.

The new unwashed cable tests, curves Nos. 1, 3 and 6, show the 1.125-in. cable better in proportion than the other unwashed cables. This is partially due to the fact that the 1.49-in. cable was rained on slightly before the first loss measurement was obtained. This is known to raise the loss of a new cable the first time that it occurs.[1] Further, the 1.125-in. cable had aged in storage for three years before erection, which could have lowered its loss somewhat.

*Insulator Loss Data.* Curve 1 of Fig. 8 gives the loss on one of the insulator and shield assemblies that was used to support the 1.125-in. conductor. Since the loss was practically zero up to 160 kv. to neutral, no correction for insulator loss was necessary.

Curve No. 2 is the loss curve for the insulator assembly used on the 1.49-in. and the 2.0-in. cables, shown in Fig. 10. From observing this curve it can be seen that the insulator loss is practically zero for voltages to neutral of 200 kv. (346 kv. line). Thus this insulator string showed practically no corona loss over the voltage range where the 1.49-in. cable was tested. However, the low loss range of the 2.0-in. cable covers practically the same range as the loss curve for the insulator string. This correction was applied to all of the data on the 2.0-in. cable equal to the loss on the proper number of insulator assemblies involved.

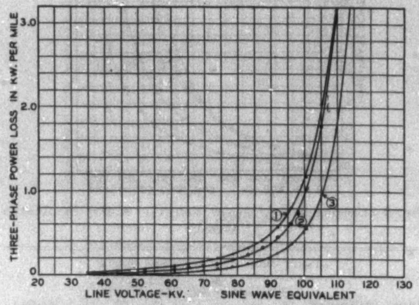

Fig. 9—Corona Loss Curves Showing Effect of Configuration and Transpositions

No. 2 wire—used cable, weathered surface

| Curve No. | Barometer in. hg. | Temperatures deg. fahr Dry bulb | Wet bulb | Cable | Date | Spacing in ft. | Configuration |
|---|---|---|---|---|---|---|---|
| 1 | 30.07 | 52 | 46 | 55 | 12- 1-31 | 5.05 | Flat |
| 2 | 30.07 | 53.5 | 47 | 57 | 12- 1-31 | 5.05 | Flat<br>Transposed |
| 3 | 29.92 | 54 | 45.5 | 60 | 11-27-31 | 6.3 | Triangular |

*Flat, Triangular, and Flat Transposed Spacings.* It was desired to determine whether there was a change in the loss on lines due to the configuration. A three-phase line of No. 2 wire was erected with a total length of 1,050 ft. The loss was measured on this line for a horizontal spacing of 5.05 ft. and an equivalent triangular spacing of 6.4 ft. The loss curves as obtained for these two conditions were in rather close agreement. The lower loss value, however, was on the triangular spaced condition as seen by curve No. 3 of Fig. 9. Curve No. 1 shows the loss value for the horizontal line. This change in loss is slightly greater than could be attributed to daily variation changes or any change in the surface of the wire due to handling, and appears to be a valid decrease in the loss.

A further attempt to determine the effect of transposing was studied. The line was broken into three equal sections so that there was a complete barrel or a complete transposition section. The loss as determined on this transposed line is given in curve No. 2, and is practically the same as that for the untransposed line, as given in curve No. 1. The very slight difference in the curves could be accounted for by the daily variation as observed on other cables.

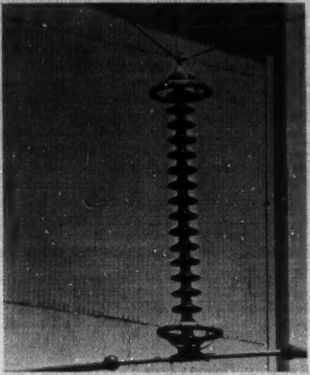

FIG. 10—INSULATOR ASSEMBLY USED ON THE 1.49-IN. AND 2.00-IN. CABLES

### CONCLUSIONS

Further evidence proves that the die grease and other foreign matter, existing on cables as received from the manufacturers, greatly increases the corona loss, and that this loss can be partially eliminated by washing the cable with a solvent, soap solution and thoroughly rinsing in water.

The cleaning of the cable surface by scratch brushing only slightly lowers the corona loss below that which exists on a new cable properly washed.

The polishing of a cable surface by buffing temporarily decreases the loss on the cable below that which exists on a new cable properly washed.

Dragging a clean cable a distance of one-half mile increases the loss on the cable above that which is found on a washed cable, but the loss is less for this condition than for the new, unwashed cable as received from the factory.

The surface of clean washed cables, that have been subsequently dragged, ages rapidly; so that with a year of weathering the loss is practically the same as found on a new, washed, undamaged cable.

The surface produced by buffing ages rapidly, and as observed over one week's time, showed a great variation in loss which was not regular but at times approached the loss value as found for the new, washed cable.

The variation in corona loss as found on new, washed cables shows that the voltage shift for the same power loss on cables of different sizes is practically proportional to $r \log S/r$, which is the factor in $E_0$ which is varied by dimensions.

Insulator loss, if not considered, may introduce an appreciable error in corona loss measurements at high voltages. The loss can be partially eliminated by properly shielding the insulator strings.

A completely transposed line 1,050 ft. long showed the same corona loss as the same length of line untransposed. A horizontally spaced line showed a slightly higher loss than the same length of line with the equivalent triangular spacing.

### ACKNOWLEDGMENTS

Two of the conductor specimens used in the tests reported in this paper were donated to the Harris J. Ryan Laboratory about three years ago.

The 1.125-in. hollow copper cable was donated by the Anaconda Wire and Cable Co.

The 2.0-in. hollow aluminum cable was donated by The Aluminum Company of America.

The obtaining of these data was greatly facilitated by the help of graduate students who showed their interest in the work by their willingness to help whenever needed.

## Appendix

### DESCRIPTION OF CONDUCTORS

All of the cables used in the test were new unused cables on the original reels which came from the factory. The No. 2 wire used in the transposition test was hard drawn, copper wire.

The 1.125-in. diameter cable was hollow copper of the I-beam type construction. This was a single-layer cable with 24 strands in the one layer. The strand diameter was 0.125 in. The diameter of the supporting twisted I-beam core was 0.875 in.

The 1.49-in. diameter cable was a double-layer, hollow-core, copper cable of the I-beam type construction. The diameter of the strands in both layers was 0.0971 in. The diameter of the supporting twisted I-beam core was 1.100 in. The inner layer contained 37 strands and the outer layer contained 43 strands.

The 2.0-in. diameter hollow aluminum cable was a single-layer cable, with the strands supported by a flexible-tube center. The outside diameter of this flexible tube was 1,636 in. The outside layer of the cable was of 30 strands of aluminum with a strand diameter of 0.182 in.

## Bibliography

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2. *The Hysteresis Character of Corona*, by Harris J. Ryan, and H. H. Henline, A.I.E.E. TRANS., Vol. 43, 1924, p. 1118.

3. "Dielectric Phenomena in Electrical Engineering," by F. W. Peek Jr., 1929 Edition.

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## Discussion

**Wm. S. Peterson:** In applying the results of these very accurate measurements of corona loss to the actual design of a line, we find that the conditions along the line, such as altitude, temperature and other conditions, are not the same as those at the laboratory, where the investigations had to be made. In the laboratory each variable must in general be investigated separately, and then these effects must be united by some statement of physical law connecting them. From this a more nearly correct estimate can be made for actual line conditions.

The economically important part of a corona loss curve is the region of lower losses. It will be recalled that the early work of Mr. F. W. Peek on this subject gave us a formula that was more applicable to the upper part of the corona loss curve. Our need for some method of calculating corona loss for the lower value of losses, as well as the higher values, leads to the development of a theoretical formula modified by empirical correction that should be of interest to engineers dealing with corona. Due to lack of space, the mathematical derivations and experimental corrections will not be given in detail. Only the results and method will be described.

*Loss Formula.* The corona loss was considered to be the loss due to charging current flowing radially through the corona envelope. The drop in voltage through the envelope was assumed as being the integral of the potential gradient from the point where the gradient in air exceeded 53.6 kv per inch effective values, to a point on the conductor at some higher value. Instantaneous values of current and voltage were used. For the portions of the cycle where the voltage is too low to cause air breakdown, no loss was assumed to occur. It is realized that this theory is rather crude. Much dependence is placed on the further empirical corrections.

As a result of this theory the following formula was evolved:

$$P_c = \frac{0.0000337\, f E_n^2}{(\log_{10} s/r_1)^2}\,[4.606 \log (E_n/E_0) - 1 + (E_0/E_n)^2]$$

Where $P_c$ is the corona loss in kilowatts per mile per conductor, $f$ is the frequency, $s$ is the equivalent conductor spacing in inches, $r_1$ is the radius of the conductor in inches, $E_n$ is the voltage to neutral in kv, and $E_0$ is the disruptive voltage in kv at which the voltage gradient at the surface of the conductor is equal to the air breakdown value.

The importance of the above equation is that it leads to the suggestion that from actual tests an empirical curve might be determined that would replace the terms in the brackets, if they should not give a curve that accurately fits the test data. In other words, the empirical modification of the theoretical formula would be a curve derived from tests that would be a function of the ratio $E_n/E_0$ and would be the same for all cables and conditions.

Examination of corona test data indicated that the theoretical formula gave quite close results for voltage ratios in the vicinity of 1.3. However it did not fit the curves as closely as desired for the entire range of voltage.

Plotting of the results of a great many corona loss curves, taken by many investigators over a wide range of conditions revealed that the empirical modification suggested above could be made and be in agreement with over 90 per cent of the curves.

Corona loss is then given by

$$P_c = \frac{0.0000337\, f E_n^2}{(\log_{10} s/r_1)^2}\,(\phi_c')$$

where $\phi_c'$ is a value taken from the accompanying curve Fig. 1, and is a function of the ratio $E_n/E_0$, and is spoken of as an empirical corona loss function.

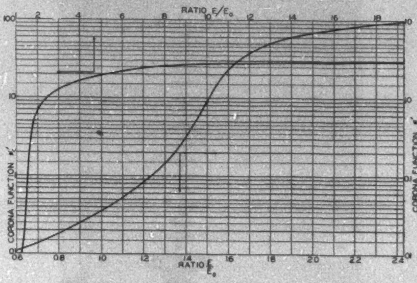

FIG. 1—EMPIRICAL CORONA LOSS FUNCTION FOR CALCULATING PURPOSES

It will be noted in the formula that the loss is considered to vary directly as the frequency. This is the theoretical result. It also agrees quite closely with some of Mr. Peeks early work, where his experiments indicated the loss would vary directly with the frequency. It is not the intention of this discussion to maintain that the corona loss with direct current will be zero. For commercial frequencies, 25 cycles and above, it is believed that good accuracy will be obtained by using the value in the formula.

*Disruptive Voltage.* For smooth round conductors, the value of $E_0$ as calculated by Mr. Peek's formula was used, with a slight modification for air density, which will be discussed later.

$$E_0 = 123.4\, m\, \delta^{2/3}\, r \log_{10} s/r. \text{ (kv to neutral)}$$

where $m$ is a roughness factor; $\delta$ is the air density factor and is equal to [17.9 by barometer inches/(459 + fahrenheit degrees)]; $r$ is the radius of the conductor and $s$ is the equivalent spacing, both in the same units.

For stranded conductors it was considered desirable to attempt to develop a new formula that would take account of the stranding so that the factor $m$ would not have to be used for that purpose, and thus leave $m$ to take care of the individual strand conditions.

Omitting the development, the formula for $E_0$ for cables with 12 or more strands in the outside layer is as follows:

$$E_0 = \frac{123.4\,\delta^{2/3}\,m\,[\log (s/cr_i) + (n-1) \log 2s/(d - 2cr_i)]}{1/cr_i + (n-1)/(d - 2cr_i)}$$

(kv to neutral)

where all log terms are to the base 10, $r_i$ is the radius of an individual strand; $n$ is the number of strands in the outside layer of the cable, and $c$ is a quantity given by

$$c = \left[ 1 - \frac{\sin (\pi/2 + \pi/n)}{\pi/2 + \pi/n} \right]$$

Certain simplifying assumptions were made in the development of the above formula so that it is not accurate for a small number of outside strands. For the special case of cables with six outside strands, the following formula was developed.

$$E_0 = \frac{123.4\,\delta^{2/3}\,rm\,[\log s/r + 0.0677]}{1.37} \text{ (kv to neutral)}$$

*Air Density Factor.* Recently at the Ryan High Voltage Laboratory at Stanford University, Mr. Victor Siegfried conducted some corona tests dealing with a conductor in a tank, in which the atmospheric conditions could be controlled. These tests provided data on the effect of pressure, temperature and humidity.[1] Also at the same place, Mr. Alexander Nuttall conducted some corona tests in which the temperature of the conductor was varied through a wide range.[2] A study of their results revealed that the most practical variation of $E_0$ to use, as the air density was varied, was as $\delta^{2/3}$. On the basis of these tests and further verification from general corona tests, by various investigators, it was decided to use this value in the calculations of $E_0$ that have been given. It was also concluded that the temperature of the conductor should be used rather than the temperature of the air.

*Roughness or Condition Factor.* The roughness factor $m$ has been simplified in that it is related to the condition of the individual strands, however it has been found it must also take account of whether the conductor has been weathered, or washed, or is in the condition represented by new unwashed cables, which have been discussed by Mr. Carroll and Mr. Cozzens. The effect of humidity on its value has not as yet been entirely determined.

Most of the tests run by Mr. Carroll and Mr. Cozzens were in the afternoon when humidity was low. It was a time of day when corona losses were probably at their minimum values.

For new unwashed cables in these tests, the value of $m$ as used in the foregoing formulas ranges from 0.67 to 0.74. After washing, the range for all sizes of cable tested was very narrow varying from 0.912 to 0.93. By scratch brushing the value of $m$ was reduced to 0.885. By buffing the value of $m$ was raised to an average of 1.00. The dragged and dusty cable had a value of $m$ of 0.72 to 0.75. As this cable was weathered it gradually improved until after five months it attained a value of $m$ of 0.945.

For general purposes it is felt that the proper value of $m$ to use with low humidity and with the wire well weathered or in good clean condition is approximately 0.92. During the night with low humidity this value may go as low as 0.78. A general value that was used for comparison with test data, where the conditions were not known exactly, was 0.90. This gave very good results. For general line design a value of $m$ between 0.87 and 0.90 is probably correct.

It is anticipated that as further information becomes available on corona loss, the wide range of conditions that have to be taken care of by the condition (roughness) factor $m$ will be reduced and that formulas will become available to account accurately for many conditions that are not well understood at the present time. It is also probable that a greater number of accurate experiments under controlled conditions will furnish data whereby the curve giving the corona loss function may be more accurately determined.

At the present state of knowledge concerning corona, the method of predetermination of corona loss outlined in this discussion has served quite well to give accurate curves for practical engineering purposes. Excellent agreement with a great variety of tests has been obtained.

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[1] "The Effect of Atmospheric Conditions on Corona Loss." (Thesis)

[2] "The Effect of Conductor Temperature and Various Surface Conditions on Power Loss Due to Corona on Conductors at High Voltage." (Thesis)

# The Triple-Harmonic Equivalent Circuit in Three-Phase Power Transformer Banks

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***Synopsis.***—*The importance of triple-harmonic voltages and currents in electrical power systems is generally recognized by engineers associated with the power and telephone industries. It is desirable to have some convenient method of representation and calculation of the triple-frequency effects in three-phase power systems.*

*The path of the third-harmonic current is different from that of the fundamental current and for this reason the circuit can be considered as separate and distinct. The characteristics of the triple-frequency circuit as determined by laboratory experiment are given in this paper. Methods of measurement of the required quantities for accurate solution of the triple-frequency circuit are described. The results of an experimental investigation of the equivalent triple-frequency circuit as proposed by H. S. Osborne in 1915 are set forth. A typical simple three-phase power network has been set up and the measured currents compared with computed values. Oscillograms are presented of voltages and currents with typical transformer connections demonstrating the principles of operation of the circuit both for normal and abnormal excitation conditions. The effects of various types of connected loads are discussed, with particular attention given to the condition of triple-frequency resonance. It is shown that triple-frequency resonance occurs when the external capacitive reactance of the circuit is equal to the triple-frequency no-load impedance of the transformer. Resonance produces large triple-frequency currents and serious distortion of the line-to-neutral voltage of the system.*

* * * * *

## INTRODUCTION

THE lack of symmetry existing between the curves of instantaneous voltage applied to a transformer and the resulting exciting current was first demonstrated by Harris J. Ryan in 1889[1], and since that time much has been written on the subject from different view points. The importance of a clear understanding of the action of harmonic currents arising from the varying permeability of transformer steel cores in polyphase circuits is universally recognized. Because of a number of undesirable effects resulting from the behavior of triple-frequency voltages and currents in present day power transmission and distribution systems, it has become of considerable importance to the power and telephone industries to be able to predict, with a fair degree of accuracy, the value of these triple-frequency quantities in a particular system, with a view to their proper control. In the past only rough approximations have been used for estimating the amount of harmonic current which would result from various transformer connections on power systems. It was believed that it would be possible to calculate accurately in a simple manner the value of such currents if sufficient information were available. Working on this assumption, transformer and other circuit constants were carefully determined in the laboratory, then these transformers were connected in a manner similar to that used in practise and the harmonic currents in the circuit measured. These measured values were compared with values obtained by analytical calculation.

The path of the triple-frequency current and all multiples of the third-harmonic current is different from that of the fundamental current so that the circuit actually becomes a separate and distinct one. This paper will be devoted mainly to a brief discussion of this circuit which will be termed "the triple-harmonic circuit." An experimental proof of its equivalent representation is presented with suggestions as to its use, behavior and limitations.

## PRODUCTION OF HARMONIC CURRENTS

The well-known fact that when a true sinusoidal voltage is applied to a transformer the resulting exciting current is not sinusoidal is shown in Fig. 1. Upon analysis it is found that this exciting current contains harmonics of 3rd, 5th, 7th, etc., order (the amount of the harmonic component decreasing as the frequency increases). It is a well established fact that the distortion of the current wave results from the varying permeability of the transformer steel core. It also must be admitted that any harmonic component of current can exist only as the result of a corresponding harmonic of e.m.f. in the circuit. In the oscillogram shown, the wave form of the generator supplying the voltage to the transformer was almost perfectly sinusoidal. The resulting conclusion must be that the transformer itself, due to the action of its

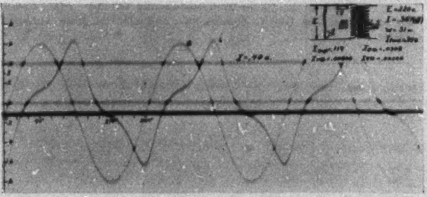

FIG. 1—THE APPLIED VOLTAGE AND EXCITING CURRENT FOR A 3-KVA. TRANSFORMER

steel core, produces the various harmonic components of voltage which cause the harmonics of current present in the transformer exciting current.

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1. For references see Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

The above fact is made evident by the suppression of any frequency of harmonic current. For example, by using similar transformers with a star connection on the primary with isolated neutral the triple harmonic currents are all in phase when considered acting in the direction toward the neutral, (*i. e.*, they are 3 × 120 deg. = 360 deg. apart, or in phase toward the neutral) and consequently are suppressed. In this case the transformer generated triple e.m.f. appears in the total wave of voltage across the terminals of a single transformer. Such triples of voltage will appear in all windings of the transformer if no connections exist except this primary one. If now the secondary windings be delta-connected the triple voltages in each winding will be added directly in phase in the circuit around the delta. This means that before closing the delta there will exist across its open ends a triple harmonic of voltage which is three times the triple voltage of each transformer secondary coil. Upon closing the delta this voltage is short-circuited through the three no-load triple-frequency transformer impedances of the secondary windings in series. A corresponding triple-frequency current flows around the delta. Whenever this current is permitted to flow it has a direct demagnetizing effect upon the flux which produces its e.m.f. because it lags this e.m.f. by 90 elec. deg. The action is similar to the demagnetizing effect in a polyphase alternator under short-circuit conditions where the armature current is mainly limited by the demagnetizing effect of armature reaction.

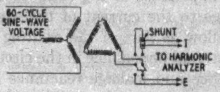

FIG. 2—CIRCUIT FOR MEASURING THE TRIPLE-FREQUENCY NO-LOAD IMPEDANCE OF A TRANSFORMER

In the transformer, the triple harmonic of current may exist in any winding in which the connections give a path permitting it flow. It is also common to have it divided among the windings with a part flowing in each. This of course depends upon the transformer connections.

## TRANSFORMER IMPEDANCE MEASUREMENTS

If computations of triple harmonic currents are to be accurately made it is necessary to have complete information regarding: (a) the triple-frequency voltage generated in a transformer with the triple harmonic of current suppressed, (b) the transformer impedance to this current and, (c) the leakage impedance of the different windings.

All values obtained were reduced to the common basis of 220 volts which was used for all cases.

*Generated Voltage.* Measurements of the generated triple-frequency voltage in a transformer were obtained by connecting a bank of three similar transformers star-delta as shown in Fig. 2 with one corner of the delta left open and the open ends connected to a high resistance circuit of a harmonic analyzer.

This was obtained by throwing the double-pole switch of the figure in the down position. A true sinusoidal fundamental voltage wave was applied to the transformer bank primary. The secondary triple voltage was measured for different values of applied voltage and a curve drawn as shown in Fig. 3. The generated voltage per transformer is one-third the total voltage measured.

*No-Load Impedance.* By closing the delta through a low resistance shunt, (*i. e.*, by closing the switch in the up position), readings of the triple current could also be obtained on the analyzer. The ratio of triple-frequency voltage per transformer to the triple-frequency current circulating in the closed delta gives the transformer total impedance to this current at the saturation of the core determined by the fundamental applied voltage. These values are shown by the "no-load impedance" curve on the diagram. The effect of the leakage impedance of the winding was not considered in this measurement because of its insignificance in comparison with the quantity measured.

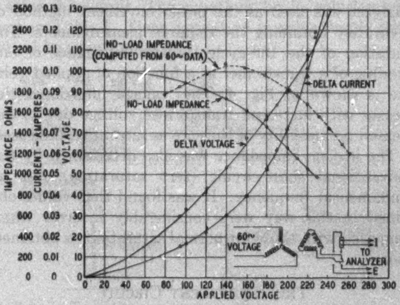

FIG. 3—THIRD-HARMONIC NO-LOAD IMPEDANCE OF 3-KVA. TRANSFORMER

(All values per phase and referred to 220-volt base)

Oscillograms of the open-circuit delta voltage and closed-circuit delta current were taken, with each oscillogram record containing a fixed triple-frequency reference wave. From these oscillograms the phase angle of the no-load impedance was obtained for rated transformer voltage.

In order to ascertain if sufficiently accurate values of the triple-frequency no-load impedance could also be determined from fundamental frequency measurements, the no-load 60-cycle impedance of a single transformer was determined in the conventional manner by the application of a fundamental sinusoidal voltage to the single transformer winding and measurements taken of current and power. The 60-cycle reactance thus measured was changed to a 180-cycle reactance and the impedance plotted as shown on the diagram. The inaccuracy of this latter method is clearly evident.

*Leakage Impedance.* The leakage impedance of each transformer winding was measured by means of a method described by O. G. C. Dahl.[15,19] The harmonic analyzer was used as the most convenient method of accurately obtaining the required measurements. The variation of the 180-cycle leakage impedance of one winding of a transformer as a function of applied voltage is shown in Fig. 4. The leakage impedance decreases with increased transformer voltage due to decreased permeability of the core as saturation increases.

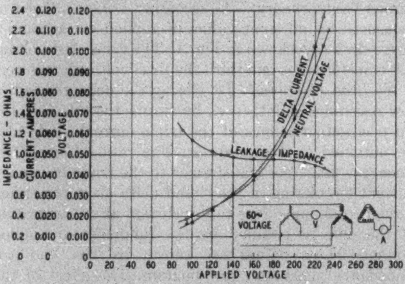

FIG. 4—THIRD-HARMONIC LEAKAGE IMPEDANCE OF 110-VOLT WINDING OF THE 3-KVA. TRANSFORMER

(All values per phase and referred to 220-volt base)

The leakage impedance was also determined by the conventional short-circuit (zero saturation) test at fundamental frequency. It was found that values obtained in this way were considerably in error when compared with those for normal saturation as obtained above.

## THE EQUIVALENT CIRCUIT

In order to determine in three-phase power systems the magnitude and distribution of the third harmonic components of the exciting currents it is desirable to have some convenient method of calculation. The conventional transformer equivalent circuit has been found to be most accurate and convenient for calculating currents and voltages at fundamental frequency. An adaptation of this circuit for application to triple-frequency components of transformer exciting currents was made by H. S. Osborne in 1915.[8] This circuit provides a simple and convenient method of representation of the action of the triple-frequency effects. However, no proof could be found that its accuracy had been established, and it was felt that laboratory measurements showing the integrity of calculation by its use would be of real value.

The representation of the equivalent triple-frequency circuit for a transformer as given by Mr. Osborne, is shown in Fig. 5. This is a T-network similar to the general transformer circuit except for the addition of the generator. The shunt leg consists of a third harmonic generator in series with the no-load impedance. The voltage of this fictitious generator is the triple-frequency component of e.m.f. which exists in the terminal voltage of a single transformer when the third harmonic component of exciting current is entirely suppressed. The no-load impedance is the ratio of the triple-frequency voltage to the current of the same frequency which would flow as part of the exciting current considering no external impedance in the circuit.

The resistance and leakage reactance marked with the subscript *p* represent values of the primary winding while those marked by *s* refer to the secondary coil. The no-load values are marked *nl*. The e.m.f. of the third harmonic generator is designated by *E*.

It will be noted that in this equivalent circuit the amount of the triple-frequency current is mainly determined by the value of the generated e.m.f. and no-load impedance, while its division between the primary and secondary circuits may be largely determined by their relative values of leakage impedance.

In the equivalent circuit different transformer connections may be represented as follows:

If the primary were connected star with no neutral connection, the line *b* would be open and so no third harmonic of current could flow in it, but if a neutral connection is provided, the points *a* and *b* will be closed through an impedance. The type of impedance will depend upon the power source.

If the primary winding were connected delta, the points *a* and *b* would be short-circuited through the leakage impedance furnishing a closed path for the third harmonic current. Similarly, if the secondary winding were a closed delta the points *c* and *d* would be short-circuited. Should the delta be closed through an impedance of any kind, this would be inserted between the points *c* and *d*. It is evident from the equivalent circuit that if both primary and secondary windings were connected delta the third harmonic of current would divide between them inversely as their respective leakage impedances.

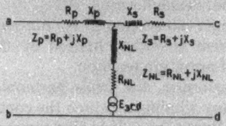

FIG. 5—THIRD-HARMONIC EQUIVALENT CIRCUIT

With the secondary star-connected the method of representation would be similar to that for the same primary connection. Should the load be connected from line to neutral it would also be represented between the terminals *c* and *d*. If the line capacitance is appreciable it will furnish a path for the triple-frequency currents when the neutral is grounded, and therefore would be considered as a capacitance load between the points *c* and *d*.

From the above discussion, it is evident that this equivalent circuit is applicable to all connections where third harmonic currents flow due to the inherent characteristics of the transformers.

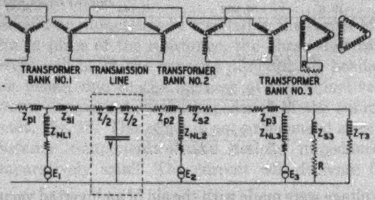

Fig. 6—Equivalent Representation of a Transmission System

The manner in which the equivalent circuit may be applied to various transformer connections on a power system is shown in Fig. 6.

## Equivalent Circuit Tests and Results

In order to test the validity of the third-harmonic equivalent circuit, a series of measurements was taken on a typical power-system network. These measurements were then compared with the computed values obtained from a solution of the equivalent circuit representing the network. Since it was impracticable in this investigation to conduct tests on an actual power transmission system, laboratory apparatus was set up in the electrical machinery laboratory at Stanford University to represent practical conditions.

The network used in this test is shown diagrammatically in Fig. 7. Power was supplied by a 52-kw. sine-wave alternator directly coupled to a synchronous motor. Normal 60-cycle sinusoidal voltage was applied to the primary of a star-star bank of 3-kva. transformers. This bank in turn supplied a bank of 2-kva. transformers which was connected star-delta, the neutral being connected to the secondary neutral of the first bank of transformers. The bank of transformers connected to the incoming power lines was used for the purpose of obtaining a fixed reference wave for the oscillograms. The third-harmonic neutral current circulating between the transformers and the synchronous motor was recorded at the top of all oscillograms for reference purposes.

Various types of impedance were placed in the corner of the delta circuit of the 2-kva. transformers, to determine the effect of different loads on the triple-frequency circuit under actual operating conditions. With this connection it should be noted that a particular value of impedance inserted in the corner of the delta will have the same effect upon the third-harmonic component of the transformer exciting current as the same impedance connected as a balanced three-phase load on any star-connected winding of the transformer bank with neutral connection. For example, an impedance of some value $Z$ inserted in the corner of the delta connection corresponds to an impedance $Z/3$ per phase on the star-connected primary winding assuming one-to-one transformation ratio.

Known values of resistance, inductance, and capacitance were inserted separately in the corner of the delta winding, and for each case the third-harmonic currents in the neutral and in the delta were measured on a harmonic analyzer. The analyzer readings were checked by a thermocouple ammeter, and in most cases the two agreed very closely, showing that the currents were almost entirely third-harmonic or 180-cycle. This was also verified by oscillograms of the neutral and delta currents.

For each case in which measurements were taken, the neutral and delta currents were computed by means of the equivalent circuit, Fig. 7. Having previously determined the 180-cycle voltages generated in the transformers and the no-load impedances and treating leakage impedance as negligible, it is necessary only to include the value of external impedance for $Z_3$ in order to solve the circuit. The equations for its solution are given in Table I. Their derivation is quite simple and will not be given here.

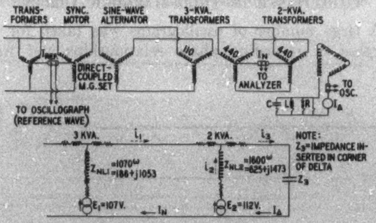

Fig. 7—Test Circuit and Its Equivalent Circuit

The results obtained from the series of tests are shown in Table I. The values computed by the equivalent circuit method agree very well with the measured values. In nearly all cases the agreement is within 5 per cent, which may be considered accurate enough for most purposes. It will be noted that for the cases of low external impedance, the error is small and that as the impedance is increased the disagreement somewhat increases. For the case of high capacitive reactance, which is nearly equal to the no-load impedance of the transformer, the error is 50 per cent.

These errors are due almost entirely to differences in saturation as a result of triple-frequency current changes

TABLE I—TABULATED RESULTS—EQUIVALENT CIRCUIT TEST

(See Fig. 7) $Z_1 = 186 + j1053$
$Z_2 = 625 + j1473$

| External impedance per transformer ($Z_3/3$) | | Delta current $I\Delta$ amperes | | | Neutral current (per transformer) $I_n$ amperes | | |
|---|---|---|---|---|---|---|---|
| Type | Value | Measured | Computed | % diff. | Measured | Computed | % diff. |
| Short | Zero | 0.170 | 0.169 | − 0.6 | 0.102 | 0.100 | − 2.0 |
| Short | Zero | 0.172 | 0.169 | − 0.6 | 0.103 | 0.100 | − 2.9 |
| Res | 151 + j0 | 0.155 | 0.156 | + 0.6 | 0.0913 | 0.0922 | + 1.0 |
| Res | 182 + j0 | 0.150 | 0.152 | + 1.3 | 0.0900 | 0.0901 | + 0.1 |
| Res | 306 + j0 | 0.133 | 0.139 | + 4.5 | 0.0800 | 0.0822 | + 2.8 |
| Res | 307 + j0 | 0.132 | 0.139 | + 5.3 | 0.0800 | 0.0822 | + 2.8 |
| Ind | 0 + j 161 | 0.141 | 0.136 | − 3.5 | 0.0840 | 0.0802 | − 4.5 |
| Cap | 0 − j 36.3 | 0.182 | 0.178 | − 2.2 | 0.108 | 0.106 | − 1.9 |
| Cap | 0 − j 269 | 0.280 | 0.278 | − 0.7 | 0.167 | 0.166 | − 0.6 |
| Cap | 0 − j1062 | 0.460 | 0.231 | −49.8 | 0.282 | 0.141 | −50.0 |

Equations
(For Circuit See Fig. 7)

$$I_1 Z_1 - I_2 Z_2 = E_1 - E_2 \quad (1)$$

$$I_1 + I_2 = I_3 \quad (2)$$

$$I_1 = \frac{E_1 (Z_2 + Z_3) - E_2 Z_3}{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3} = I_n$$

$$I_3 = \frac{E_1 Z_2 + E_2 Z_1}{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3} = I_\Delta$$

$$I_3 Z_3 = V \quad (3)$$

$$I_1 Z_1 + V = E_1 \quad (4)$$

$$I_2 = \frac{E_2 (Z_1 + Z_3) - E_1 Z_3}{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3}$$

$$V = \frac{Z_3 (E_1 Z_2 + E_2 Z_1)}{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3}$$

both in magnitude and phase angle. A small change in the saturation of the steel core causes variation in the transformer constants, resulting in errors in the computed values. It is also possible that an error exists as a result of assuming the generated voltages $E_1$ and $E_2$ of Fig. 7 to be in exact phase. A difference in the degree of core saturation in transformers of the two banks might be responsible for a phase difference between them.

## EFFECTS OF RESISTANCE, INDUCTANCE, AND CAPACITANCE IN THIRD-HARMONIC CIRCUIT

A large number of oscillograms was taken for the purpose of recording phase relationships and wave distortion for different conditions of loading of the third-harmonic circuit. When a comparison of records is made for two conditions of loading, any change in phase angle is determined by comparing the position of the two waves with respect to the fixed reference wave appearing at the top of each record.

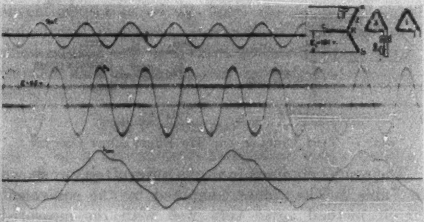

FIG. 8—DELTA VOLTAGE (REVERSED) AND LINE CURRENT WHEN NO THIRD-HARMONIC CURRENT FLOWS

It should be noted here that all oscillographic records of voltage were made with the aid of an inverted vacuum tube.[20] The inverted vacuum tube draws no current from the circuit to which it is connected, and consequently does not disturb conditions in that circuit.

When the third-harmonic component of exciting current is suppressed a third harmonic of flux is produced within the steel core of the transformer. This flux causes the triple-frequency voltage shown in Fig. 8. In this oscillogram the voltage is reversed due to the inverted vacuum tube connection. Distortion in the phase voltage of each transformer winding resulting from the suppression of the third-harmonic current, is shown in Fig. 9.

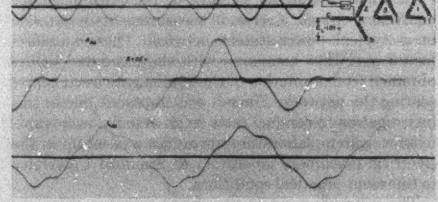

FIG. 9—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT WHEN NO THIRD-HARMONIC CURRENT FLOWS

If the normal third-harmonic current, Fig. 10, is allowed to flow, normal excitation results and the phase voltage wave shape is identical with that of the applied voltage as shown in Fig. 11. For this condition the third-harmonic component of current (which is required by the core to produce a sine-wave of flux) flows in the delta circuit, and therefore a sine-wave of voltage appears across the winding of the transformer.

If additional resistance now be inserted in the delta circuit it is to be expected that the triple-frequency current will shift ahead in time phase with respect to its original position and will, at the same time, decrease in magnitude. This assumption, which results from an analysis of the equivalent circuit, is verified by an oscillogram taken for this particular case, Fig. 12. This shift in phase and decrease of the current means that the current is no longer in the proper position or of sufficient magnitude to cause a sine-wave of flux to exist in the core. Hence a resultant third-harmonic flux will exist, giving rise to a third-harmonic voltage across each phase.

Should an inductance be inserted in the corner of the delta in place of the resistance, the phase shift of the current will be in the opposite direction, or behind in time phase, due to the increase of the inductive reactance component of the impedance of the complete circuit, Fig. 13. This effect is not pronounced since the resistance component of the no-load impedance is comparatively small. The current will decrease from its normal value and will, as before, cause a resultant third-harmonic voltage to appear in the transformer voltage wave as a result of the distorted flux wave.

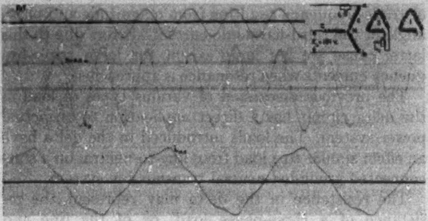

FIG. 10—DELTA CURRENT AND LINE CURRENT WITH NO EXTERNAL IMPEDANCE

When a capacitance is placed in the delta circuit an opposite condition from that of the inductance is encountered. Instead of increasing the total impedance of the circuit, the effect of the capacitance is to decrease it. It is evident that a small value of capacitive reactance in the delta will cause the third-harmonic current to be larger in magnitude than the normal value. The current will shift ahead in time phase from the normal position, Fig. 14. There are now two factors contributing to the distortion of the flux wave; first, the shift in phase position, and second, the increase in magnitude of the current above the normal value required for a sine-wave of flux. The latter effect causes a direct magnetizing force upon the core, and the flux caused by this current now magnetizes the core in such a manner as to produce a third-harmonic flux in the same direction as that flux which the core generates when the third-harmonic current is suppressed. Consequently, the third-harmonic voltage generated by this resultant flux will be larger in value and will cause a greater distortion in the total voltage wave across the winding. This is clearly shown in Fig. 15.

### THIRD-HARMONIC RESONANCE

From the above oscillograms and a study of the equivalent circuit, it is apparent that a capacitance in the delta circuit giving a corresponding value of capacitive reactance equal to the no-load inductive reactance of the transformer will cause a condition of resonance when the current will be limited only by the equivalent resistance of the circuit. Fig. 14 is an oscillogram of the delta current and line current when the above resonance conditions were approached. Note the large distortion of both currents.

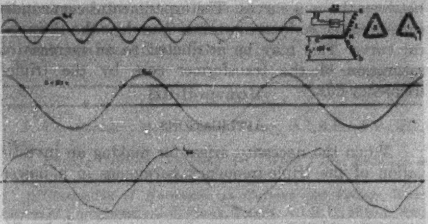

FIG. 11—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT WHEN ONE DELTA IS CLOSED

In order to determine this condition of resonance experimentally, a series of readings of delta current was taken as the value of capacitance was varied over a wide range. From these readings, a curve was plotted showing third-harmonic current as a function of capacitance. The resulting curve is shown in full line in Fig. 16. The shape of the curve indicates that a condition of resonance actually does exist, and that for a certain value of capacitance the current rises sharply to a high value. For the resonance condition the distortion of the flux will be a maximum, and the saturation of the steel core at triple-frequency will be extremely high. Fig. 15

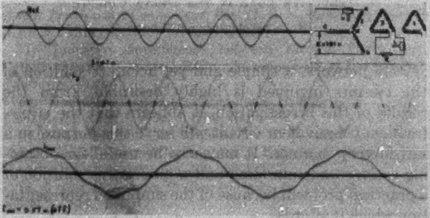

FIG. 12—DELTA CURRENT AND LINE CURRENT FOR A RESISTANCE LOAD OF 2,461 OHMS IN THE DELTA CIRCUIT

shows the large distortion in the transformer voltage when resonance is approached.

Assuming the normal no-load impedance of the transformer to remain constant, a theoretical resonance curve was computed over the range covered by the experimental curve and plotted in Fig. 16. Agreement in the two curves is not obtained near or at the point of resonance. Computation on the basis of the equivalent circuit does not take into consideration the change in saturation which actually occurs under these abnormal conditions which accounts for the lack of agreement between the two curves. The experimental curve indicates a lower no-load reactance than does the theoretical curve. This may be attributed to an increase of saturation of the transformer core by the triple-frequency flux.

## APPLICATIONS

When the necessity arises for making an investigation of the triple-frequency harmonics in a power system network, a simple and yet accurate solution of the circuits involved is highly desirable. From the results of this investigation, it appears that the triple-frequency equivalent circuit will serve this purpose in a satisfactory manner. It may also be useful for obtaining a clear understanding and a qualitative solution of a practical problem because of the simplified representation which it affords.

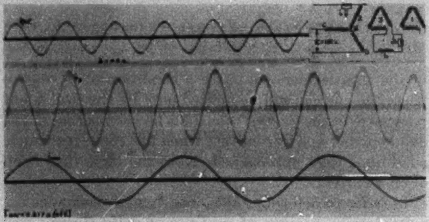

FIG. 13—DELTA CURRENT AND LINE CURRENT FOR AN INDUCTIVE LOAD IN THE DELTA CIRCUIT

($X_l$ = 290 ohms; $L$ = 0.77 henrys)

Since the triple-frequency circuit is a distinct and separate one, it should be a relatively easy matter to solve most network problems, although in some cases the networks may be too extensive to permit of a simple solution. In all calculations, it should be kept in mind that the triple-frequency no-load and leakage impedances are not constant quantities, and hence must be measured at the particular value of saturation applying to the problem under consideration. This is also the case for the triple-frequency generated voltage. The variation of these quantities as a function of fundamental applied voltage is very clearly brought out by the curves of Fig. 3. The assumption that the generated voltages in transformers of different banks of a system are in phase may lead to errors. Line drop resulting from fundamental frequency load currents may cause the triple-frequency generated voltage to be considerably out of phase. The value of the no-load impedance also may change due to core saturation effects at triple-frequency resulting from magnitude and phase angle of the third-harmonic current. Errors due to this latter cause are not large except for large triple-frequency currents when resonance is approached.

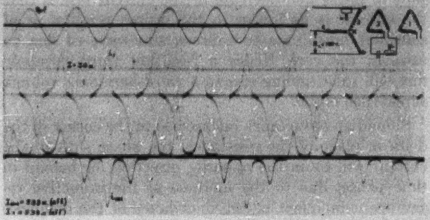

FIG. 14—DELTA CURRENT AND LINE CURRENT FOR A CAPACITIVE LOAD IN THE DELTA

($C$ = 2.0 $\mu$f.)

The previous discussion of various types of load in the delta circuit has a direct application to an actual power system. The loads introduced in the delta have an effect similar to a load from line-to-neutral on a star-connected grounded-neutral transmission system.

The resistance in the delta may represent the resistance of a three-phase load, or of the line and grounded neutral return circuit of the star-star connected transmission system. Generally, line resistances are comparatively small and may not be of large practical importance in the triple-harmonic circuit.

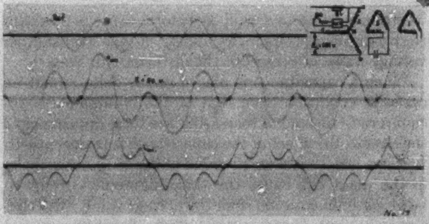

FIG. 15—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT FOR A CAPACITIVE LOAD IN THE DELTA

($X_c$ = 1,572 ohms; $C$ = 1.69 $\mu$f.)

The external inductance inserted in the delta may be compared to the inductance of a load or of the line conductor. Here again line reactances are usually small compared with the no-load reactance of transformers and their effect on the third-harmonic voltages and currents may be slight.

For the case of the capacitance, the practical application is of considerable importance. The capacitance inserted in the delta gives the same effect as does the capacitance-to-neutral of the line conductors. A relatively small value of capacitance is necessary to produce a resonance condition, since the no-load reactance of the transformer is high. This is the actual condition which may exist on a transmission line, due to the fact that the capacitance from line-to-neutral (ground) is relatively small. Thus a resonance condition of third-harmonic current may actually occur on a transmission system if the line capacitance happens to be of the proper value. If resonance does exist on a system, a large third-harmonic current will flow, and dangerously high voltages may appear across the transformers. Also a large third-harmonic current tends to cause bad inductive interference in neighboring communication lines.

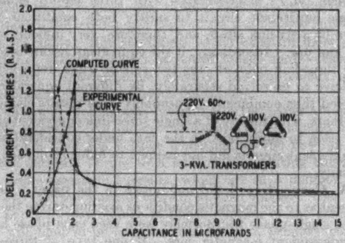

Fig. 16—Third-Harmonic Resonance with Capacitance Inserted in Delta

### Conclusions

From the results of this investigation, the following conclusions have been drawn.

1. The equivalent circuit as adopted with the inclusion of a triple-harmonic generator is a true representation of actual conditions existing in a transformer.

2. The triple-frequency equivalent circuit may be used to solve triple-harmonic network problems, provided the necessary data are available. Practically the only limitation to its use is the complexity of the network.

3. The equivalent circuit solution will be very accurate for conditions in which the third-harmonic excitation is normal or nearly so. For cases in which the system voltages are abnormal, either in wave form or in magnitude, the no-load impedance and "generated" voltages of the transformers must be determined for these particular conditions of saturation before a high degree of accuracy can be expected from the equivalent circuit solution.

4. Third-harmonic resonance will occur on a system when the external equivalent capacitive reactance of the circuit is equal to the no-load inductive reactance of the transformer at triple-frequency.

5. Third-harmonic resonance results in abnormally large triple-frequency currents which produce transformer core saturation at this frequency thus changing the no-load impedance of the equivalent circuit.

6. Resonance at triple-frequency produces a large distortion of the system line-to-neutral voltages which may have dangerously high maximum values resulting in insulation breakdown.

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## Discussion

**P. W. Blye:** Although, in general, triple harmonic components from transformers are smaller than those arising in rotating machinery operated with grounded neutral,[1] in some cases the former have had an important bearing on the inductive coordination of power and telephone systems. The paper of Professor Morgan and Messrs. Bairos and Kimball is therefore of interest from that standpoint. The problem of harmonics from transformers has been recognized by Project Committee 1C on Wave Shape of the Joint Subcommittee on Development and Research —N.E.L.A. and Bell System, and that committee is at present engaged in a rather extensive investigation of the wave-shape characteristics of transformers.

My experience with several sets of tests on transformers similar to the tests made by the authors bears out their general conclusion that, at a given excitation or over a narrow range of excitations, the equivalent T-network described in their paper presents a simple and accurate method of dealing with triple harmonics arising in two-winding transformers. One or two points brought out in the paper incidental to the general conclusions, however, are not in agreement with my experience.

The paper states that the total leakage impedance as measured by the usual short-circuit method (multiplied by the order of the harmonic if measured at fundamental frequency) was found to be considerably in error as compared to the sum of the individual leakage impedances used in the equivalent circuit and observed at normal excitation by the delta-opened-delta method. My experience is that this is not necessarily the case. Consider, for example, a small 60-cycle, three-phase shell-type model transformer on which a number of such tests have been made. In the case of two windings located near the center of the core window of the model transformer, the difference between the total leakage impedance determined from a short-circuit test and the sum of the individual impedances at normal saturation amounted to not more than 1 to 2 per cent. The total leakage impedance observed with 140 per cent normal voltage applied was found to be of the order of only 4 or 5 per cent less than in the short-circuit test. Even in the extreme case of two windings located at opposite ends of the core window immediately adjacent to the yoke, the difference between the total leakage impedance under short-circuit conditions and the sum of the individual impedances at normal saturation was found to be only about 2.5 per cent. At 140 per cent normal voltage the total leakage impedance of these two windings decreased to about 15 per cent less than in the short-circuit test.

The paper also makes a statement to the effect that the individual leakage impedances decrease with increasing excitation. While this appears to be more or less generally true of the total leakage impedance, in certain cases the leakage impedance associated with one winding of a two-winding transformer has actually been found to increase slightly with increasing excitation.

Fig. 6 of the paper implies that the triple harmonic equivalent circuit of a three-winding transformer may be developed very simply from that of a two-winding transformer by merely adding a third branch made up of the individual leakage impedance of the third winding.

Boyajian has demonstrated[2] that, with respect to load currents, a three-winding transformer may be resolved into a convenient three-terminal network. Such a network could, no doubt, be developed for use in considering triple harmonics arising from an external source as, for instance, from a grounded neutral generator, which completely override those arising in the transformer. This network, however, as pointed out by Boyajian, does not apply to magnetizing currents. Test data which I have seen bear out the idea that the leakage impedances in a three-winding transformer are not quantities which can be associated definitely with the individual windings, even at a given excitation, irrespective of the condition of the other windings. As far as I know, a satisfactory and reasonably simple equivalent circuit for harmonics arising in a three-winding transformer which would be generally applicable, irrespective of the method of connection of the various windings, has not yet been devised.

Fig. 16 of the paper illustrates very well the dependence of the shunt element of the equivalent circuit, called by the authors the "no-load impedance," upon the third harmonic excitation. The difference between the calculated and measured resonance point is no doubt due to the change in the "no-load impedance" for the condition of resonance due to the abnormally large third harmonic current circulating in the secondary.

**A. Boyajian:** Referring to Fig. 6 of the paper, a single equivalent circuit for Bank No. 3 is not applicable to both the currents produced by $E_3$ and for those produced by $E_2$. The division of leakage reactance between $S_3$ and $T_3$, will be to a first approximation rather independent of $P_3$ but dependent on the core; whereas, the division of leakage reactance between $S_3$ and $T_3$, so far as $E_2$ is concerned, will be independent of the core but dependent on $P_3$ in accordance with three circuit equations. A single equivalent circuit to satisfy both conditions would have to be a six-link affair, and, therefore, very difficult to construct and use. Accordingly, if the equivalent circuit is to be a simple three-link network, the two sets of triple frequency currents have to be solved separately, by different equivalent circuits, and then combined. Reasonably good results claimed by the authors, with the use of a single three-link equivalent circuit, would seem to imply that, in the case under consideration, the two equivalent circuits did not happen to differ from each other materially.

**H. V. Carpenter:** I did not notice in the paper a definite statement as to the magnetic conditions existing during the tests. If three single-phase transformers were used each phase had its own independent magnetic core. If one type of three-phase transformer was used the three flux paths would be partially but not wholly independent while if the other type was used any flux passing through one core returned through the other two.

In this latter case the third harmonic flux would find no return path. It seems likely that the three different conditions would give somewhat different results.

**D. I. Cone:** Despite the number of publications dealing with the behavior of triple harmonics arising in three-phase circuits due to transformer magnetization, there still appears to be a need for the presentation of methods for quantitative prediction of the behavior of given networks. This paper is a helpful contribution toward that end.

Considering Fig. 3 and the related discussion, it is noted that a "no-load" impedance of about 1,050 ohms is obtained at normal voltage. An approximation to this value is obtained from the single-phase test data of Fig. 1, which indicates a third harmonic current of 0.119 amperes at 220 volts, combined with an assumption for the "open circuit" third harmonic voltage. If this be taken as 50 per cent of the 60-cycle voltage, a value of 925 ohms is obtained. This value, of course, includes the third harmonic impedance of the 60-cycle source, but evidently provides a much closer approach to the third harmonic impedance value than an attempt to obtain it from the 60-cycle reactance of the transformer.

Referring to Fig. 16, it is most encouraging to observe that even at the resonance point it was practicable to predict the approximate magnitude of the third harmonic current.

Desirable extensions of this study would concern the distribution of triple harmonics in three-winding transformers and associated lines.

**L. J. Corbett:** In the triple-harmonic circuit the current and voltage relations are rather complex. The triple-harmonic voltage is superposed upon the fundamental frequency voltage at a particular phase relation, and triple-harmonic currents flow in a circuit which is also carrying fundamental-frequency current. The so-called triple-harmonic impedance of a transformer will vary, therefore, because of the changing state of saturation of the core, a rough average existing for each value of fundamental-frequency voltage. If the phase relations of the triple-frequency to the fundamental-frequency quantities change, the triple-frequency impedance changes also. Further, the demagnetizing effect of the triple-frequency current in the transformer is the important feature in measures for suppressing the flow of triple-harmonic currents in power systems having grounded neutrals. The open-delta voltage divided by the closed-delta current seems rather inexact as a measure of the triple-harmonic impedance existing under actual operation.

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[1] See *Telephone Interference from A-C. Generators Feeding Directly on Line with Grounded Neutral*, by J. J. Smith, A.I.E.E. Trans., Vol. 49, No. 2, April 1930.

[2] *Theory of Three-Circuit Transformers*, A. Boyajian, Trans. A.I.E.E., Vol. XLIII, 1924.

The equivalent circuit method is convenient, and is fairly accurate when the elements are single transformer banks separated by impedance, as in the tests described in the paper. However, because of the demagnetizing effect, one transformer bank connected $Y/Y$ with grounded neutral will force but little more triple-harmonic current through two $Y$/delta banks (with grounded neutral) of a given size than it will through one. Two equal $Y/Y$ banks will force practically twice as much triple-harmonic current through one $Y$/delta bank as will one of them alone, though the triple-harmonic voltage and outside impedance remain the same. For conditions which exist on most power systems *i.e.*, multiple banks at power houses and substations and divided triple-harmonic circuits, the equivalent circuit method of calculation has serious limitations.

The data and oscillograms presented in the paper are of considerable interest. An important feature which should not be overlooked is that the voltage which causes the flow of triple harmonic currents is due to a lack in the exciting current of simple triple-harmonic currents, which are in a definite phase relation to the fundamental wave of applied voltage. (See Fig. 1 of the paper.) Any change in phase relation of the secondary triples will tend to be compensated for by a primary triple of such magnitude and phase that the resultant triple-harmonic ampere turns will be such as would be required in the primary exciting current to reproduce the applied fundamental-frequency voltage wave.

**E. G. Cullwick:** In this paper the authors state that the harmonics in the exciting current of a transformer are produced by voltages of like frequency produced in the transformer itself, "due to the action of the steel core." I do not think that this is a very good description of what actually happens. If the applied voltage is truly sinusoidal, then the induced emf in the transformer will be almost exactly sinusoidal, and will require a sinusoidal flux variation for its generation. Due to the varying reluctance of the iron core, the magnetizing current necessary to produce this flux will not be sinusoidal but will contain a strong third and higher odd harmonics. To represent these harmonics in an equivalent circuit it is logical to replace the varying impedance of the transformer by a constant impedance and a generator of odd harmonics, but I do not think that it is accurate to state that the harmonics are actually due to emf's generated in the transformer windings.

The third harmonic emf's appearing in the secondary phase voltages of transformers with their primaries connected in star without a neutral lead are caused by a third harmonic in the flux which is due to the suppression of the third harmonic in the exciting current. This third harmonic is necessary if a sinusoidal flux variation is to be obtained, and its absence will cause the flux-wave to contain a third harmonic. With a core-type three-phase transformer these harmonic fluxes cannot exist. Have the authors considered this case in connection with the equivalent circuit diagram?

Were any measurements made for the ninth and higher harmonics, and also were the third harmonic measurements entirely free from the effects of these higher harmonics?

**C. W. Frick:** The paper gives the results of an experimental study of the triple harmonics in three-phase transformer banks. It will be noted that measurements were made with a harmonic analyzer. This method permits a wider range of measurements and gives better accuracy than methods previously used for measuring the triple harmonics. The authors compare the experimental results with the results calculated for the equivalent circuit for the triple harmonics in a two-winding transformer proposed by H. S. Osborne in 1915 and used by several investigators. It seems to the writer that the limitations of the equivalent circuit brought out by the experimental data in the paper should be considered further.

In examining the equivalent circuit it is well to keep in mind the actual behavior of the triple harmonics. A single path for the triple-harmonic exciting current in a three-phase bank of two-winding transformers can be provided by connecting one of the windings delta and connecting the other winding so that it is open-circuited for the triple harmonics. If the impedance of the delta winding is zero the triple-harmonic voltage is zero. If the impedance of the delta winding is appreciable a triple-harmonic voltage sufficient to overcome the impedance voltage due to the triple-harmonic exciting current is set up. If the impedance is increased, for instance by adding impedance in one corner of the delta winding, a larger triple-harmonic voltage is required. Furthermore, the triple-harmonic exciting current with appreciable impedance in the delta winding is different from the triple-harmonic exciting current with zero impedance because it requires a different exciting current to set up the necessary triple-harmonic voltage. In the equivalent circuit the behavior of the triple harmonics is represented by a constant triple-harmonic voltage ($E$) acting through a high impedance designated $Z_{NL}$ in Fig. 5 of the paper. If there is only one path for the triple-harmonic current the equivalent circuit has only one of its branches closed and it amounts to a simple series circuit; impedance in the actual path (delta winding) is represented by impedance added in series.

In the paper an equivalent circuit is set up using values of the voltage $E$ and the impedance $Z_{NL}$ determined experimentally under specified conditions. The results show that the equivalent circuit set up in this manner behaves very nearly like the actual circuit when the added impedances are such that the triple-harmonic exciting current does not differ greatly from the normal value, as might be expected. The data also show, however, that the equivalent circuit may not behave like the actual circuit with impedances which require a triple-harmonic exciting current differing materially from the normal value. This shows that the equivalent circuit is subject to limitations which should be kept in mind.

The impedance $Z_{NL}$ has been shown from theoretical consideration to correspond to the open-circuit self-inductive reactance of one winding in a 1-to-1 ratio transformer where the leakage is small; this shows the order of magnitude.[3] A distinction must be made between the effective magnetizing reactance for the third harmonic and the effective magnetizing reactance for the fundamental because the core passes through a wide range of inductance values. It is shown in the paper that the value of $Z_{NL}$ for the third harmonic cannot be taken as three times the open-circuit reactance for the fundamental but must be determined in some other manner. The equivalent (internal) impedance obtained for the third harmonic varies with the magnitude and phase of the third-harmonic circuit which flows. The authors use an impedance value obtained under specified test conditions. Three transformers are connected $Y$ on the primary side and delta on the secondary side, as in Fig. 2 of the paper, and the ratio of the triple-harmonic voltage per transformer with the delta opened to the triple-harmonic current in the closed delta is called the "no-load" impedance for the triple harmonics at the particular excitation voltage used. In many instances where the transformers are available for making this test it may be almost as easy to set up a circuit similar to the actual circuit being studied and measure the exciting current directly. The equivalent circuit would then be superfluous.

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[3] The constants of the equivalent circuit are discussed in a paper by A. Boyajian entitled *Resolution of Transformer Reactance into Primary and Secondary Reactances*, A.I.E.E. Trans., 1925, p. 805.

The increase of the third-harmonic exciting current with added capacitance within a certain range in the delta winding which has been observed by other investigators is discussed in the paper. It appears from the equivalent circuit as if resonance might occur between the added capacitance and the impedance $Z_{NL}$ at the frequency of a triple harmonic. The impedance $Z_{NL}$ does not appear in the actual circuit. The equivalent impedance which it represents varies with the magnitude and phase of the triple-harmonic current as pointed out above and true resonance cannot exist. It would seem preferable to consider the behavior observed merely as a condition of distortion without reference to resonance.

The leakage impedances associated with the windings may be of more value for some purposes than the "no-load" impedance. Fig. 4 of the paper gives values of leakage impedance associated with one of the windings and shows the variation with excitation voltage. It would be of interest to compare this with the leakage impedance associated with the other winding which is not given in the paper and to compare the sum of the two with the total leakage impedance for the two windings. In tests made by the writer the leakage impedances associated with the two windings varied with the excitation voltage but their sum remained about the same over a wide range of excitation voltages. The arrangement of the core and windings of the transformers tested would also be of interest.

**T. H. Morgan:** There is a considerable divergence in the manner in which triple-harmonic phenomena in transformers are viewed by various people. However, many of the conceptions of the phenomena involved, which at first thought appear to be at variance, are found to be reasonably in accord when fully analyzed.

The authors agree with Mr. Blye that it is not necessarily true that the total leakage impedance of a transformer as measured by the usual short-circuit method will always be higher than the correct value. It happened to be so in the case investigated by the authors, but it would seem that the amount of this discrepancy would depend on the proportion of the leakage flux passing through the transformer core and the degree of saturation of the core by the main flux.

The explanation of the inaccuracy involved by the use of the single three-link network equivalent circuit in Fig. 6 to calculate currents from all sources in a three-circuit transformer, as pointed out by Mr. Blye and Mr. Boyajian, is quite justified. However, it should be clearly understood that this circuit is not the one used in the test described in this paper. It was given only as an illustration of the application of the equivalent-circuit method to a practical case. The actual circuit investigated contained no three-circuit transformer and is given in Fig. 7 of the paper. Consequently the small discrepancies shown by the authors between their test and computed values cannot be charged to this account.

In reply to the question of Professor Carpenter regarding magnetic conditions of the test it should be made clear that individual single-phase transformers were used in each bank on the test.

Mr. Corbett believes that the triple-harmonic impedance as obtained by the authors will prove to be inexact when the phase angle of the triple current changes. This is contrary to the results of the investigation, as the authors show that measurements over the complete range of 180 deg for the triple-harmonic current give values having close agreement with the computed currents on the basis of constant impedance. The application of the equivalent-circuit principle to the case of multiple banks on a power system appears to offer no particular difficulty and should give reasonably correct results when correctly applied.

The question of the manner in which we view the cause of the harmonic currents has been interestingly discussed by Professor Cullwick. The viewpoint expressed by the authors is arrived at from the following reasoning. The harmonic currents are purely superimposed phenomena. It is impossible to obtain a current of any frequency in a circuit without an emf as its cause. With a true sinusoidal voltage applied to a transformer we have harmonics of current in the exciting current. Since the harmonics of voltage which cause them are not present in the generator they must exist in the transformer. As an example, consider the simple case of a single two-circuit transformer with the secondary winding open-circuited and true sinusoidal voltage applied to its primary circuit. If the leakage impedance of the primary winding and also the impedance of the generator be considered zero, there would be no harmonic voltages in the transformer. However, if this circuit has any impedance whatever as in the practical case the transformer supplies the harmonic voltage required to force each component of harmonic current through the circuit. In other words, the harmonics of current are a result of harmonics of emf in the transformer.

Measurements were made by the use of a harmonic analyzer which gives a high degree of accuracy for the measurement of any harmonic entirely uninfluenced by the effects of other harmonics. Certain measurements were made for the ninth and other harmonics but an analysis has only been made for third-harmonic effects, these being by far the most important because of greater magnitude.

The remarks of Mr. Frick suggest a number of points for discussion. The assumptions involved by equivalent circuit representation can possibly be explained by comparing the action of the triple-frequency transformer flux with that of the flux in a polyphase non-salient pole alternator. If we consider such an alternator armature circuit having extremely low leakage reactance and resistance we have a circuit which is closely analogous to the triple-frequency circuit in the transformer. The alternator armature open-circuit condition can be compared to that of the transformer having the path for the triple-frequency current blocked in all windings. If the alternator armature be short-circuited the flux will be reduced to a very low value by armature reaction which corresponds to the case of a closed-delta on the transformer bank where the triple-frequency path is short-circuited. These may be considered the two limiting conditions. Various other effects of armature reaction can be obtained in the alternator by inserting different amounts and types of impedances in the armature circuit. This corresponds to inserting external impedance in the delta or in any other circuit of the transformer permitting the flow of triple-frequency current. In this latter case the amount of the current and flux will change with the amount of the impedance while the phase angle will be governed by the kind of impedance used in either the alternator or the transformer circuit. Under these conditions if the armature reaction effect in the case of the alternator be treated as a constant reactance for various amounts and angles of armature current it will be equivalent to the treatment of the "no-load impedance" ($Z_{NL}$) of the transformer as a constant for all conditions of triple-frequency current. Theoretically such an impedance will not be a perfectly constant quantity for either the alternator or the transformer as it will vary somewhat with current magnitude and phase angle. As a matter of fact the investigation of the authors shows clearly that the impedance ($Z_{NL}$) remains practically constant over a wide range of magnitude and phase angle of the triple-frequency current. Also the investigation very clearly brings out that we do get a condition of resonance (see Fig. 16) which is in rather close agreement with the calculated phenomenon on the basis of constant $Z_{NL}$. The point of resonance occurs when the external capacitive reactance equals $Z_{NL}$. At this point we would expect the greatest error in the method because of the extremely high triple-frequency currents. The last point in Table I corresponds to such conditions and the error is easily explained by referring to the curves in Fig. 16 near the point of resonance.

# Radio Plant of R.C.A. Communications, Inc.

BY H. H. BEVERAGE,* C. W. HANSELL,* and H. O. PETERSON*
Associate, A.I.E.E. Associate, A.I.E.E. Associate, A.I.E.E.

***Summary:***—*This paper describes the radio plant of R.C.A. Communications, Inc. Charts are given showing the growth of the services handled through this plant. Some of the technical requirements of the service are discussed and the means for meeting these requirements disclosed. In describing the facilities in use, they are divided into three general divisions, namely, central offices, transmitting stations, and receiving stations. Most of the recent development of this plant lies in the field of short wave operations, i. e., frequencies between 3,000 and 30,000 kc.*

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## HISTORICAL OUTLINE OF THE R.C.A. COMMUNICATIONS SYSTEM

THE Radio Corporation of America, through its subsidiary R.C.A. Communications, Inc., operates a world wide radio communications network between the United States and about forty foreign countries. The major terminals of the system are in New York and San Francisco. There are supplementary centers in Honolulu, Manila, and Havana.

The Radio Corporation of America opened its transoceanic services in 1920 using low radio frequency radiation, between 15 and 30 kilocycles, produced by means of Alexanderson alternators.[1,2,3] Following the discovery that a large band of high frequencies could be used for long distance communication these high frequencies have also been used since 1924. At the present time they carry nearly all the long distance radio traffic. Vacuum tube transmitters are used exclusively in producing the high-frequency radiation.[4,5,6]

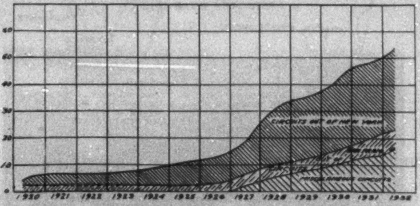

FIG. 1—GROWTH OF R.C.A. INTERNATIONAL TELEGRAPH CIRCUITS

On the Atlantic coast, at the present time, a total of about 8 low-frequency and 35 high-frequency transmitters, controlled from New York, are located at Rocky Point, Long Island, N. Y., Marion, Mass., New Brunswick, N. J. and Tuckerton, N. J.

All incoming traffic for New York is handled through a central receiving station at Riverhead, Long Island, N. Y. This station has about 16 low-frequency and 40 high-frequency receivers.[1,3,5,7,8]

On the Pacific coast 12 high-frequency transmitters, controlled from San Francisco, are located at Bolinas, California. About 20 high-frequency receivers are located at Point Reyes. There are also several low-frequency receivers located at Marshall and remotely controlled from the Point Reyes station.

Fig. 1 shows the growth in the number of circuits operated, starting with 6 in 1920 and expanding to 54 in 1932. The rapid increase in the number of circuits, after 1927, was made possible by the introduction of high-frequency equipment, the first cost of which is relatively low.

Fig. 2 is a map of the world showing the more important circuits of the R.C.A. system. This system, in conjunction with branch radio circuits and wire line networks in the countries served, reaches practically the whole civilized world.

Fig. 3 shows the growth of the R.C.A. international telegraph traffic. It is of interest to note the rapid increase in high-frequency traffic during 1927, 1928, and 1929. For the past several years practically all the traffic with South America and Pacific points has been handled on high frequencies. Low frequencies are still used across the North Atlantic, to supplement the high frequencies, because of occasional disturbance to high frequencies from severe magnetic storms over this route.

The total traffic curve shows some interesting yearly cycles. The load is minimum during the summer and reaches a sharp maximum in December, largely due to the exchange of Christmas and New Year greetings.

## CENTRAL OFFICE EQUIPMENT

All traffic operations are centralized in traffic offices conveniently located in New York City, San Francisco, and other terminals. The offices are connected by wire lines with the transmitting and receiving stations, which are usually some distance away.

Messages to be sent are transferred to paper tapes by means of perforators with a keyboard similar to ordinary typewriters. The perforated tape is then fed through automatic transmitters which impress the dots and dashes of the Continental Morse code upon the control lines to the transmitting stations.

The speed of transmission is held substantially constant over considerable intervals, the speed depending upon circuit conditions and traffic load. On busy circuits a speed of 100 to 125 words per minute is

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*Engineers, R.C.A. Communications, Inc., 66 Broad St., New York.

1. For references see Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

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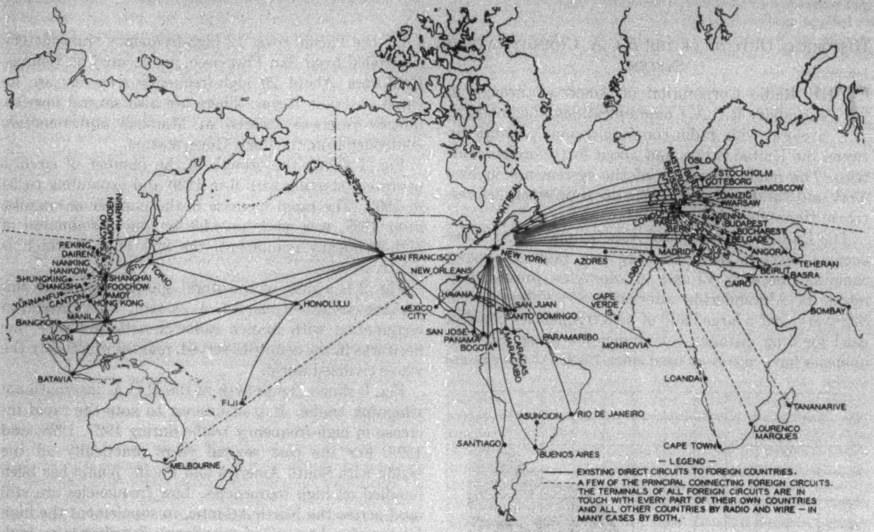
usually maintained, but speeds above 200 words per minute are occasionally used. On less busy circuits it is customary to operate at speeds of 50 to 60 words per minute so that a single operator may be capable of handling each end of the circuit.

The signals from the receiving station arrive in the central offices in the form of keyed tones. These are amplified, rectified, and then plugged through to any desired receiving table to operate an automatic recorder. The recorder has a light movable coil suspended in a strong magnetic field. Signal currents through this coil cause it to move a light lever carrying a small silver tube through which ink is impressed upon a moving paper tape. The signals appear as undulations in ink line upon the tape. Fig. 4 is an illustration of one form of recorder.


PEKING
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SHANGHAI
TOKIO
HONG KONG
MANILA
BANGKOK
SAIGON
BATAVIA
FIJI
MELBOURNE
HONOLULU
SAN FRANCISCO
MONTREAL
NEW YORK
NEW ORLEANS
MEXICO CITY
HAVANA
SAN JUAN
SANTO DOMINGO
SAN JOSE
PANAMA
BOGOTA
CARACAS
MARACAIBO
PARAMARIBO
ASUNCION
RIO DE JANEIRO
SANTIAGO
BUENOS AIRES
AZORES
CAPE VERDE IS.
MONROVIA
LISBON
MADRID
LONDON
PARIS
BERN
AMSTERDAM
BRUSSELS
OSLO
STOCKHOLM
GOTEBORG
DANZIG
WARSAW
MOSCOW
VIENNA
BUDAPEST
BUCHAREST
BELGADE
ANGORA
TEHERAN
BEIRUT
BASRA
CAIRO
BOMBAY
LOANDA
TANANARIVE
LOURENCO MARQUES
CAPE TOWN
— LEGEND —
EXISTING DIRECT CIRCUITS TO FOREIGN COUNTRIES.
A FEW OF THE PRINCIPAL CONNECTING FOREIGN CIRCUITS. THE TERMINALS OF ALL FOREIGN CIRCUITS ARE IN TOUCH WITH EVERY PART OF THEIR OWN COUNTRIES AND ALL OTHER COUNTRIES BY RADIO AND WIRE — IN MANY CASES BY BOTH.

Fig. 2—World Map Showing R.C.A. Circuits

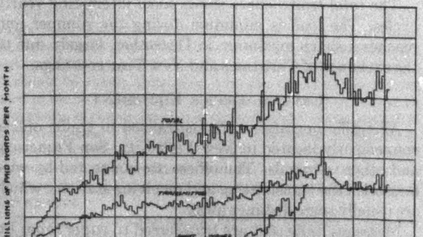

Fig. 3—Growth of R.C.A. International Telegraph Traffic

Tape bearing the signals is drawn at a convenient speed across a guide on the operator's typewriter from which the operator reads the messages and types them on message blanks. If the circuit operates faster than 50 or 60 words per minute, two or more operators may divide the tape between them. In this way the messages on all circuits are kept transcribed and there is no delay.

The typed messages are carried to a central point, on a belt conveyer, where they are timed, numbered, and routed according to destination, enveloped and dropped through a chute to the messenger room for immediate delivery.

Fig. 5 is a general view of a portion of the New York Central Office at 66 Broad Street. Two double rows of tables are shown with a belt conveyer in the center of each row. Receiving tables are arranged on one side and transmitting tables on the other. Transmitting and receiving operators handling messages with any one country are placed together to facilitate the handling of the circuits.

## TRANSMITTING STATIONS

The transmitting stations, fundamentally, are for the purpose of performing the following operations:

a. Conversion of 60-cycle a-c. power into power of radio frequencies.

b. Radiation of the radio frequency power.

c. Accurate control of radiation frequency.

d. Modulation or keying of the radiation for the transmission of intelligible signals.

For low-frequency transmission, an Alexanderson alternator, driven by a 2,200-volt, two-phase wound-rotor induction motor, is used to produce energy at 15,000 to 30,000 cycles. Its appearance is illustrated in Fig. 7. The alternator is of the inductor type with a toothed rotor running between parallel armatures bearing 64 armature coils. The outputs of the 64 coils are combined into a single circuit by means of a transformer which delivers 100 to 120 amperes at 2,000 volts to one of several downleads and tuning coils of an Alexanderson multiple tuned antenna.

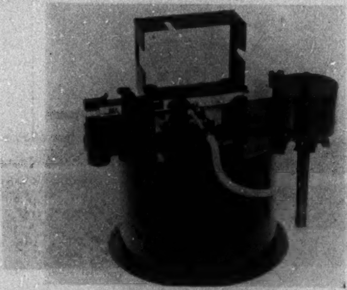

Fig. 4—A Modern Type of Ink Recorder Used on Radio Telegraph Circuits

Fig. 5—A Portion of the Operating Room at Broad Street, New York City

Fig. 6 is an illustration showing two multiple tuned antennas at Rocky Point. Each antenna consists of wires supported on towers 410 feet high, with 150-foot cross arms at the top. Each antenna is 1.5 miles long. The circulating energy in each, when a signal is being sent is about 700 amperes at 135,000 volts or nearly 100,000 kva. Although each antenna constitutes one of the lowest power factor circuits known, (for its frequency), its radiation efficiency is only about 10 per cent and it has practically no directivity.

A rather intricate system is used to control the frequency and to key the output of the alternator. In spite of its intricacy, this system has in service proved remarkably free from equipment failures. This freedom from operating difficulties is a direct tribute to the engineering skill of Mr. Alexanderson and the General Electric engineers who assisted him.

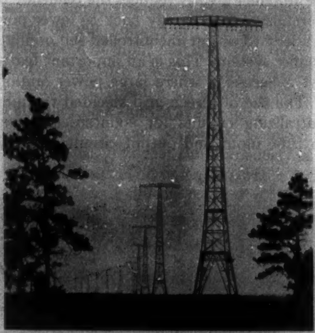

Fig. 6—The Long-Wave Antennas at Rocky Point, N. Y.

Fig. 7—Alexanderson 220-Kw. High-Frequency Alternators at the Rocky Point Station

In high-frequency transmitters, vacuum tubes are used to convert 60-cycle power into direct current and then into power of about 5,000,000 to 22,000,000 cycles. The tubes which produce the radio frequencies are equivalent to resistances, the value of which may be varied with extreme rapidity by varying the potential upon control electrodes within the tubes.

Nearly all of our high-frequency transmitters employ relatively low-power piezo electric crystal-controlled oscillators to produce initial oscillatory currents at frequencies between about 750,000 and 3,000,000 cycles.[9] The oscillator output is then passed through a chain of vacuum tube amplifiers and frequency multipliers to obtain the final power and frequency required for transmission. The crystal oscillator provides a very constant frequency and permits the operation of transmitters with relatively small frequency separation. The Federal Radio Commission limits the frequency variations to less than 0.05 per cent on old equipment and 0.02 per cent on new equipment.

The use of frequency multiplication in the successive stages of amplifier greatly reduces the tendency for high power circuits to feed energy back to lower power circuits in a way to set up uncontrolled self oscillations in the amplifier system. This is an important feature and is almost a necessity where large power amplification is used. The use of screen grid shielded vacuum tubes and neutralizing circuits for counteracting couplings between tube input and output circuits are also very helpful in preventing spurious oscillations. The final power outputs to the antennas range between about 1 and 40 kilowatts depending upon the circuit requirements.

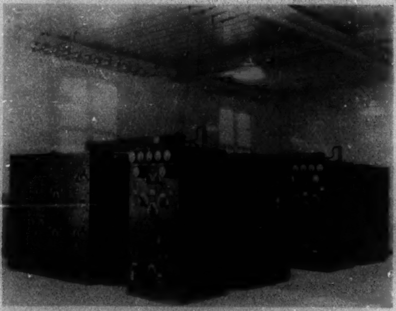

FIG. 8—A GROUP OF 20-40-KW. SHORT-WAVE TRANSMITTERS AT THE BOLINAS STATION

The keying of the transmitters in accordance with telegraph signals is done by varying the electrode potentials on some of the vacuum tubes in the chain of amplifiers. This is done through electromechanical relays or through vacuum tube devices controlled from the central office. Some of the vacuum tube keying equipment is capable of functioning at speeds equivalent to more than 1,000 words per minute, and is used at these high speeds in the transmission of pictures or "photoradiograms."

The use of high-frequency radiation, with its shorter electrical wave lengths, has made it practical and economical to direct the radiation toward the distant receiving station. Consequently, directive antennas are commonly used with high-frequency transmitters.[10]

R.C.A. Communications, Inc., has successively developed and applied four different types of directive antennas known as models A, B, C, and D. Several other types have also been designed for special requirements. The models A and B radiate vertically polarized waves while models C and D radiate horizontally polarized waves. The power gain due to directivity ranges up to 80 to 1, depending upon the type and size of antenna. Due to their relatively low cost and great directivity, antennas give a high ratio of circuit improvement per dollar of cost.

FIG. 9—THE SHORT-WAVE TRANSMITTING STATION AT BOLINAS, CALIFORNIA

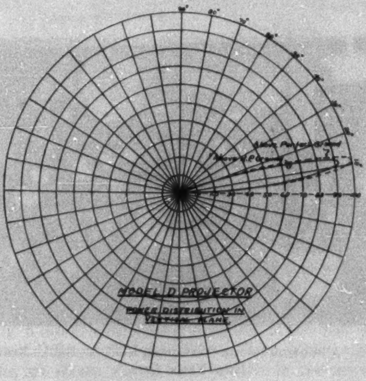

FIG. 10—POWER DISTRIBUTION IN VERTICAL PLANE FOR MODEL D ANTENNA

Figs. 10 and 11 show the directive characteristics of a two-bay model D antenna giving a power gain, over a half wave dipole at the same height as the antenna, of about 80 to 1. When used with a 40-kw. transmitter this antenna launches radiation toward the distant receiver equivalent to that which would be obtained with 3,200 kilowatts in a non-directive antenna. This is about 800 times the radiation launched toward the distant receiver from an Alexanderson alternator and low-frequency multiple tuned antenna.

Fading of high-frequency signals is a phenomenon of nature which must be overcome in a commercial radio communications system. Often the received signals vary over a great range in intensities. At times the variations are so rapid as to constitute an audio modulation, though rather slow periods of a few seconds are more common. Since it has been observed that the fading of even slightly different frequencies is not simultaneous, the effects of fading can be reduced by transmitting the same signals on more than one frequency. In some commercial transmitters the carrier wave is amplitude or frequency modulated at an audio rate, in addition to the keying, to produce side frequencies and so reduce fading by frequency diversity. However, it is preferable to reduce the effects of fading by methods applicable at the receiver such as will be mentioned later in this paper.

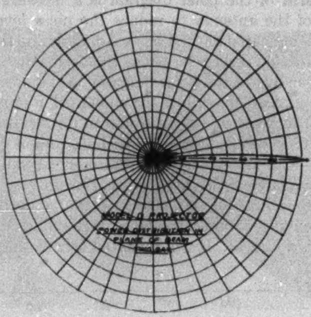

Fig. 11—Power Distribution in Plane of Beam, Two-Bay Model D Antenna

## Receiving Stations

The function of the receiving station is to select the desired signals by virtue of frequency discrimination and amplify and convert them to a form of electrical energy suitable for transmission over circuits extending to the central office. In the fulfillment of this function, several technical conditions must be effectively dealt with.

It has already been mentioned that one of the problems confronted in the operation of short wave circuits is that of signal fading. Aside from the short-period fading, which was mentioned, there are even greater ranges in intensity changes at a diurnal rate.

The diurnal variations are overcome by the use of more than one frequency channel to carry a twenty-four hour circuit. For example, the circuit from New York to Buenos Aires, operates on 20,455 kc. during daylight hours and on 8,809 kc. at night. Some of the circuits from New York to Europe require three properly chosen frequencies to insure reliable service.

The short period fading is overcome by means of automatic volume control and by a system of receiving with spaced antennas which has become known as the diversity system.[5] The spacing of these antennas is usually well over ten wavelengths. Automatic volume control is a form of automatic voltage regulation. The rectified signal is caused to react upon the overall gain of the receiver in such a manner that the gain is increased as the signal strength decreases. The relative variations of output voltage are thereby made much smaller than those of input voltage. This form of gain regulation, together with the utilization of the diversity principle, makes it possible to obtain a commercial degree of stability on a short wave circuit.

In the diversity system, advantage is taken of the fact that fading does not occur simultaneously at points geographically spaced. The extent to which fading at spaced points differs is illustrated in Fig. 12. This illustration shows a 19,180-kc. signal from Portugal as recorded simultaneously on four ink recorders at Riverhead, N. Y. The three upper strips of tape in each group were taken on single receivers connected to receiving antennas situated at spaced points. The fourth strip of tape is the result of combining the outputs of the three single receivers.

Switching arrangements are provided to allow the individual receivers of the diversity units, to be used individually, if desired. Frequently, it is convenient to leave two receivers operating on the diversity arrangement, while the third receiver is used independently to observe a second transmitter that is to be substituted.

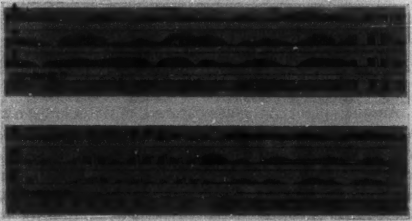

Fig. 12—Simultaneous Recorder Tapes Showing Random Fading at Three Spaced Antennas

To prevent mutual interference between the various receivers, each unit is carefully shielded and battery power to each circuit is fed through low pass filters. All receivers in a station are usually operated from a common battery system continuously charged through filter circuits.

The amount of improvement due to the use of the space diversity system is dependent upon the range of fading. Thus, if there is no fading, one antenna will do as well as three combined. If, on the other hand, the signal periodically fades to zero, no amount of gain in a single receiver can give a signal free of drop-outs, whilst the diversity system might give continuous output. In practise, the improvement due to diversity comes somewhere between these two extremes. As a general rule, a three antenna diversity system will give an improvement of approximately threefold as compared with a single antenna system.

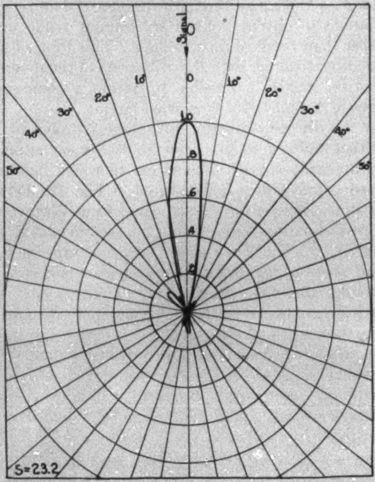

Fig. 13—Observed Horizontal Plane Directivity of Receiving Antenna

Another quality becomes apparent in the operation of a diversity system. That is, the matter of reserve apparatus on a given channel. Some of the adjustments of a short wave receiver are so critical that in making a retune, the signal might be momentarily lost due to over-shooting of the adjustment or to error of judgment. With three receivers normally carrying the circuit, any two will carry the signal fairly satisfactorily while the receiving engineer makes an adjustment of the third. This enables more continuous operation of the circuit which is important where high traffic capacity is contemplated.

To exclude as much as possible of undesired radiations such as atmospherics and locally generated disturbances, directive antennas are used. These antennas are responsive only to those signals which come from the directions toward which they are pointed. The antennas used are aperiodic, making it possible to simultaneously receive a group of different frequencies on one antenna. Their directivity, however, makes it necessary to have a number of different antennas to take care of circuits coming from different directions. At Riverhead, thirteen sets of antennas are provided. Each set consists of three spaced antennas making a total of thirty-nine.

A typical directive diagram, showing the horizontal directivity of one of these antennas, is shown in Fig. 13. This diagram was obtained experimentally by means of a transmitter carried in an airplane flying at an altitude of 1,200 feet along a circle of five miles radius about the antenna as a center.

The area of the polar diagram is a measure of the ability of the antenna to reduce the noise level. The factor $S$, indicated as 23.2 on this diagram, is the ratio of the area of the circle whose radius is equal to the greatest radius of the polar diagram to the area of the polar diagram. This ratio is the numerical improvement in signal to noise power ratio due to directivity if the noise sources are uniformly distributed about the receiving site. Expressed in transmission units, the improvement would be, in this case, 13.9 db.

The directivity in the vertical plane as determined experimentally by an airplane at three miles distance is shown in Fig. 14. It will be noted this diagram indicates a marked discrimination against radiations originating at ground level. This property is of decided importance since locally generated disturbances such as those radiated by motor car ignition systems, electrical machinery, power lines, etc., usually emanate from points at substantially ground level.

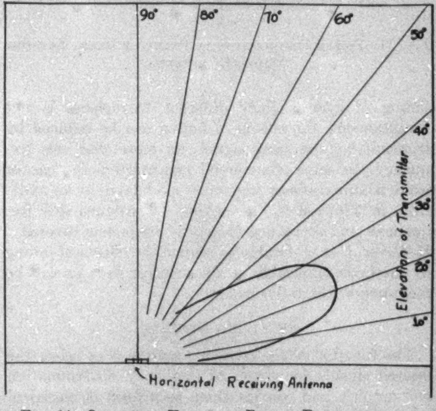

Fig. 14—Observed Vertical Plane Directivity of Receiving Antenna

In order to reduce the amount of radio frequency voltage induced directly into the transmission lines, a special design is used. In this design, four wires constitute one line, the opposite corners being connected in parallel. The electrical center of the two sides of this line are nearly coincident, and, consequently the pickup is small.

Passing into the receivers and through the tuned radio frequency amplifiers, the signals are heterodyned to audible frequencies. Most of the selectivity of the receivers is obtained in the audio frequency stages. By means of low pass filters, it has been found practical to reduce the band width to 6,000 cycles. With increasing stability of transmitter frequencies, it should eventually be possible to reduce this band width still further.

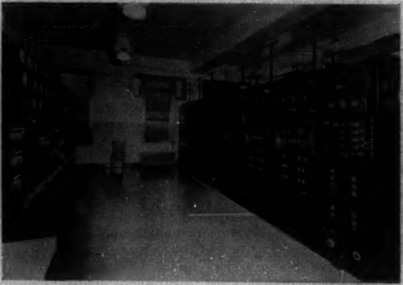

Fig. 15—Front View of Rack Containing Two Complete Diversity Telegraph Receivers, Point Reyes, California

Fig. 16 shows the tone line control board at Riverhead. All signals, both long-wave and short-wave, pass through this board. All orders from the central office are passed to the supervisor at this control board, who in turn, issues orders to the engineers at the receivers in both the short-wave and long-wave buildings, through the medium of a public address system.

By operating a telephone key, the supervisor can listen to any signal and at the same time, the volume of signal going into the line is indicated on a volume indicator. Any signal can also be monitored on an ink recorder for checking telegraphic signals, or on a facsimile visual recorder in the case of facsimile signals. The facsimile recorder is used for checking outgoing signals from Rocky Point, as well as incoming facsimile signals from London and Berlin. Due to the very high speed at which facsimile signals key the transmitter, the visual recorder is especially necessary for checking the adjustment of both the receivers and transmitters.

The principle of diversity reception has also been applied to telephony. The problem of bringing together the outputs of several antennas in such manner as to be independent of phase, is more difficult in the case of telephony than in the case of telegraphy, because of the higher modulation frequencies involved. That is, it has been found that different frequencies not only fade differently, but the phase relations between the various frequencies is often continually varying due to changes in the transmission medium. One would expect that the random changes in phase relations would increase for increasing differences in frequency, and this has been found to be generally true during disturbed conditions. Consequently, the telephonic currents received from one antenna are likely not to have any definite phase relations with respect to the currents received from a similar antenna spaced some distance away, and little is to be gained by adding the outputs of two or more receivers together during times when the fading is most severe.

In general, however, it has been found that, at any moment, the antenna with the greatest signal strength may be expected to deliver the best quality at the output of the receiver. A simple arrangement has been devised which serves to select automatically the receiver having the strongest signal. In this arrangement, three spaced antennas associated with three separate receivers, are used. The signal outputs from each antenna pass through separate superheterodyne receivers to the grids of individual second detectors. The plate circuits of these second detectors are energized by one battery feeding current through a load resistor common to all. This load resistor is connected between the negative end of the plate supply battery and ground. The audio frequency output is taken from across this load resistor. The voltage drop across this resistor is also applied, through a time constant circuit, to the control grid bias of the high-frequency amplifier tubes of all sets, thus affecting automatic volume control of all receivers simultaneously.

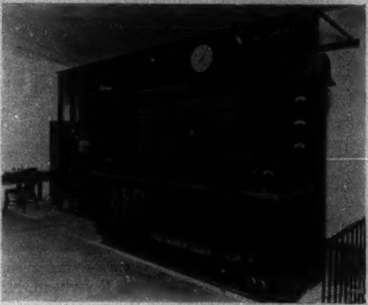

Fig. 16—Wire Line Control Board in Receiving Station, Riverhead, N. Y.

The second detectors are operated with the grids biased considerably negative, so that the output is approximately proportional to the square of the input voltage. Consequently, the detector having the greatest input will contribute most of the combined output. Thus, if the signal on one antenna is twice as strong as on another, its receiver will contribute four times as much to the combined output as will the others. Consequently, as the signal carriers fade up and down in a random manner at the several spaced antennas, the receiver with the strongest carrier reduces the output from the other receivers, and, in this manner, an effective switching action is produced. The time-constant circuit may be adjusted to operate at any desired rate in order to handle different classes of fading.

The diversity telephone receiver just described has been used for some time at Riverhead, L. I.; Point Reyes, California; and Koko Head, Territory of Hawaii, for handling addressed program material for international broadcast purposes. Many of these programs have been put on the coast to coast networks of the National Broadcasting Company and the Columbia Broadcasting Company during the past two years.[12]

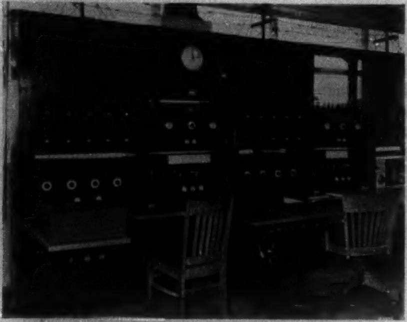

FIG. 17—A PORTION OF THE FREQUENCY MEASURING LABORATORY, RIVERHEAD, N. Y.

### FREQUENCY MEASURING

With the increasing necessity for operation of channels within narrow limits of frequency tolerance, it has become essential to have apparatus set up for accurately measuring the frequency of any given radio signal. Precision apparatus is now set up at Riverhead, N. Y.; Rocky Point, N. Y.; and Point Reyes, California, for making such measurements. (Fig. 17) The measurements are made by a process of direct comparison with the harmonics of a base frequency of 100 kc. generated by a crystal controlled oscillator of high stability. The local standard is known to be accurate to considerably better than one part in one million and the observational errors are made negligibly small.[11]

At Riverhead an average of approximately six thousand measurements per month are made with two operator's positions. Not only have these measurements been found very useful in supervising the performance of our transmitters, even as distant as Manila, but they have been indispensable in resolving such cases of interference as occur on our various circuits by providing ready and reliable information as to the stations involved. This is available not only as of the time the interference is experienced, but, also from thousands of routine measurements which are regularly taken and supplied to the R.C.A. Central Frequency Bureau. At the Frequency Bureau, continuous records are maintained of the history and performance of more than a thousand active high-frequency stations throughout the world. Records are also kept of the frequencies on which some 5,000 additional stations are projected or are occasionally measured.

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# Radiotelephone Experiments Over Short Distances

BY C. H. McLEAN*

Associate, A.I.E.E.

***Synopsis.****—The paper describes radiotelephone experiments that have been carried out over comparatively short distances on the North Pacific Coast during the last three years, employing equipment that has primarily been developed for Air Transport Communication. Commercial operation extending over a year has proved the feasibility of such a service where physical plant is economically impossible.*

* * * * *

RADIO is proving to be an effective means for the establishment of world wide telephone communication, because it furnishes a ready method of spanning the natural barriers over which wires either cannot be placed or can be placed with so great a difficulty as not to be economically justified. The usual application of radiotelephony is to connect the telephone networks of one continent to that of another by bridging a large intervening distance. Generally speaking, on the North American Continent at present there are very few communities of any appreciable size that are without telephone connection to the outside world. Exceptions to the above are to be found on the Pacific coast in British Columbia and Alaska where the intervening distances, although comparatively short, are of such a rugged nature as to render the use of the usual physical plant impossible from a cost standpoint.

During the year 1929, the British Columbia Telephone Company decided to attempt telephone linking of isolated communities to the north by means of radio, and at that time the pulp and paper town of Powell River, Fig. 1, was chosen for connection with Campbell River, the most northerly point reached by the British Columbia Telephone Company. It will be noted by referring to the map, Fig. 2, that telephone facilities extend from Vancouver northward by means of 32 miles of submarine cable to Nanaimo, located on Vancouver Island, and 100 miles of aerial copper to Campbell River. As far as the mainland is concerned, in a northerly direction plant does not exist beyond the immediate vicinity of Vancouver.

Powell River, nearly 40 miles distant from Campbell River, has a population of 6,000 people and was isolated as far as roads and telephone communication to the outside was concerned. An experimental radio circuit utilizing ground wave transmission was operated satisfactorily on a commercial basis for over a year. The circuit was similar to that later described with the exception that transmitters rated at 50 watts were employed, Fig. 3.

Experimental work carried on while the Campbell River-Powell River circuit was in operation indicated that reliable ground-wave transmission with 50 watts of power was not possible beyond a water distance of approximately 50 miles.

About this time much improved equipment, primarily developed for air transport communication,† became available, and this fact along with the participation and cooperation of the Northern Electric Company of Canada, made additional experimental work on a larger scale possible.

Two 400-watt aeronautical ground transmitters were secured. One was installed at a point 12 miles from Vancouver, on Lulu Island, while the second was placed on the motor yacht *Belmont*.

FIG. 1—PULP AND PAPER TOWN OF POWELL RIVER VIEWED FROM THE AIR

The transmitter consists essentially of a temperature controlled quartz crystal controlling a five-watt tube. A second five-watt tube is employed as a frequency doubler, and its output is amplified by a fifty-watt stage, which in turn operates into a single air-cooled tube rated at one kilowatt for the final stage. Incoming voice energy is applied to the grids of three fifty-watt tubes connected in parallel and modulation takes place in the plate circuit of the fifty-watt radio frequency amplifier. The transmitter has an unmodulated carrier power rating of 400 watts and is capable of complete modulation. Adjustment can be made to any frequency from 1,500 to 6,000 kilocycles. The power supply for the plate circuit of this transmitter is obtained from a three-phase rectifier employing tubes of the hot-cathode mercury-vapor type.

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*British Columbia Telephone Company, Vancouver, B. C.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

†*Air Transport Communication*, by R. L. Jones and F. M. Ryan, A.I.E.E. TRANSACTIONS 1930, Vol. 49, No. 1.

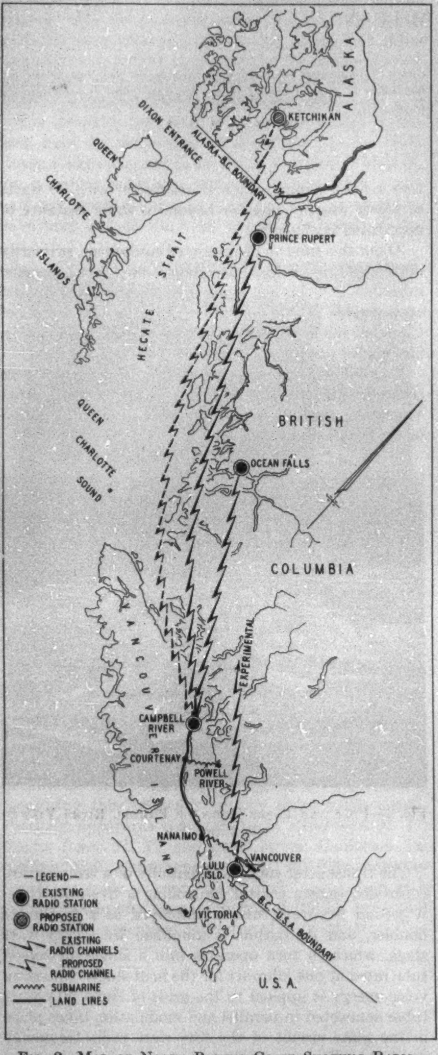
ALASKA
KETCHIKAN
DIXON ENTRANCE
ALASKA-B.C. BOUNDARY
QUEEN CHARLOTTE ISLANDS
PRINCE RUPERT
HECATE STRAIT
BRITISH COLUMBIA
QUEEN CHARLOTTE SOUND
OCEAN FALLS
VANCOUVER ISLAND
EXPERIMENTAL
CAMPBELL RIVER
COURTENAY
POWELL RIVER
NANAIMO
VANCOUVER
LULU ISLD.
VICTORIA
B.C.-U.S.A. BOUNDARY
U.S.A.
—LEGEND—
EXISTING RADIO STATION
PROPOSED RADIO STATION
EXISTING RADIO CHANNELS
PROPOSED RADIO CHANNEL
SUBMARINE
LAND LINES

Fig. 2—Map of North Pacific Coast Showing Radio Operations

The *Belmont* is 75 feet in length with accommodation for eleven people. Special masts 50 feet in height were added and a five-kva. full-automatic gasoline-driven alternator* for radio power supply was included.

The Lulu Island station consisted of a small frame building built on a sea wall at the mouth of the Fraser River. Two antenna poles one hundred and fifty feet above ground were erected. A receiver was placed two thousand feet away from the transmitter along the dyke, and terminal equipment installed to permit conversations from the *Belmont* to any telephone reached by the Vancouver long distance telephone operators.

Due to the restricted space on the yacht, it was not possible to arrange for full duplex operation, so a simplex system, similar to that used in aircraft operation, was employed.

Fig. 3—Campbell River 50-Watt Transmitter

The *Belmont* started out for the north on August 18th, 1930, and tests were continued up to the middle of October. All points of any importance between Vancouver and Ketchikan, Alaska, were visited. The skip effect of various frequencies up to 6,500 kilocycles was studied and field strength measurements were plotted for the various frequencies tested throughout the day and night. Numerous experimental calls were completed from the yacht to various points in the United States and Canada. People in Alaska talked for the first time to Chicago, New York and Montreal via the 600-mile radio circuit from the *Belmont* to Vancouver, thence by land facilities of the American Telephone and Telegraph Company to the east.

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*"Small Alternators Now Fully Automatic," by Earle R. Wetzel, *Electrical Engineering*, January 1931, Vol. 50, No. 1.

The northern trip demonstrated that not only was this type of telephone transmission practicable, but that there was a keen demand for any form of communication that would allow a telephone conversation, even if this service was restricted to a certain portion of the day.

Ocean Falls, a pulp and paper town of approximately 2,500 inhabitants and located three hundred miles north of Vancouver, was selected for the next radiotelephone installation.

The local telephone system was acquired and the 400-watt transmitter at Lulu Island was moved to Ocean Falls and placed in a small frame building one and a half miles from town. The receiver was installed in a second building one-half mile beyond the transmitter. A pole line was built carrying the necessary power and telephone facilities along the only highway. The receiver output and the input to the transmitter are carried by telephone circuits to the telephone office where the terminating and control equipment is placed.

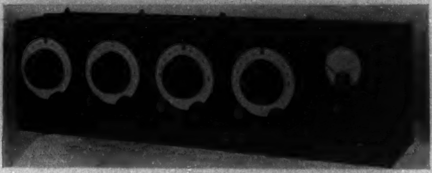

Fig. 4—Special Short-Wave Receiver Equipped with Automatic Gain Control

The transmitter and subsidiary equipment was removed from the *Belmont* and located in the Campbell River telephone office along with one terminal of the Powell River circuit still in operation. High poles similar to those at Lulu Island were erected, and as commercial power was not available, it was necessary to use the gasoline-driven alternator from the yacht.

In the course of the experimental cruise it was soon demonstrated that while the surface or ground-wave component could be relied upon for fairly steady signals, sky wave transmission was extremely erratic. Conditions of fading with the receiver at a remote unattended point resulted in very unstable operation. With average gains strong signals would cause distortion by overloading, while weak signals resulted in low levels. To take care of this condition a specially tuned radio frequency receiver, Fig. 4, with an automatic gain-control circuit was developed. This receiver was arranged to cover frequencies from 1,500 to 6,000 kilocycles and will hold the output signal to approximately ∓ two db. with an incoming radio frequency voltage ranging from 8 to 3,000 microvolts. An output level of + 14 db. is possible for 100 per cent modulation of the radio wave.

It was found extremely important that the receiver site be sufficiently isolated to minimize local interference and with this in mind, the Campbell River receiver was set up in a small frame building approximately three and one-half miles from the telephone office. Another important requirement is that the transmitter be a sufficient distance from settled areas to preclude interference with broadcast reception. At Ocean Falls it was found that a transmitter of appreciable power located in the town, even when sending on a frequency as high as 4,500 kilocycles, was picked up on the older type broadcast receivers. This was

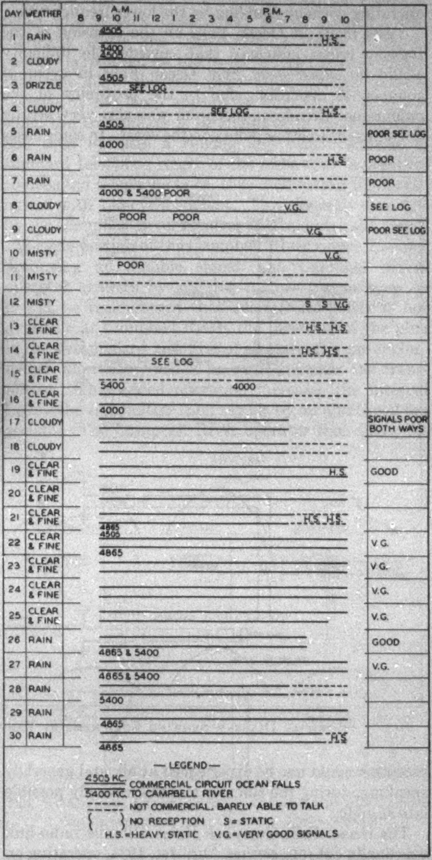

Fig. 5—Campbell River—Ocean Falls Radio Circuit Operation During September 1931

particularly true on operation at night with frequencies between 1,600 and 3,000 kilocycles. Some difficulty was experienced in completely suppressing the quartz crystal frequency which was half the carrier frequency where doubling was used. This unfavorable condition was completely eliminated by the present separation of over a mile from the nearest broadcast receiver and operating without doubling on the lower frequencies.

Tests made at Ocean Falls on the occasion of the *Belmont* cruise indicated that considerable difficulty would be experienced from Ocean Falls in event of commercial operation, due to the proximity of the mountains. Broadcast reception was also very erratic as compared to other points on the coast. In some cases reception could not be experienced at all, and generally speaking, during the summer months was only possible late at night.

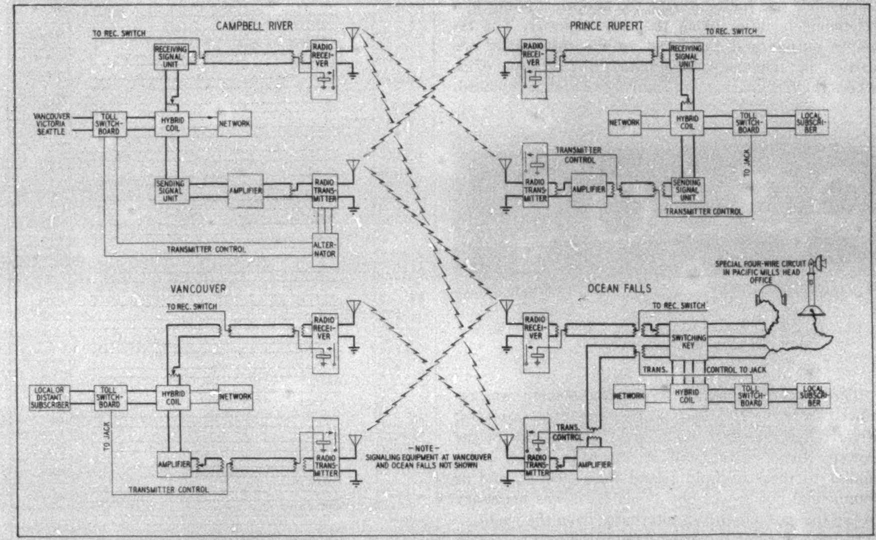
CAMPBELL RIVER
TO REC. SWITCH
RECEIVING SIGNAL UNIT
RADIO RECEIVER
VANCOUVER VICTORIA SEATTLE
TOLL SWITCHBOARD
HYBRID COIL
NETWORK
SENDING SIGNAL UNIT
AMPLIFIER
RADIO TRANSMITTER
TRANSMITTER CONTROL
ALTERNATOR
PRINCE RUPERT
TO REC. SWITCH
RADIO RECEIVER
RECEIVING SIGNAL UNIT
NETWORK
HYBRID COIL
TOLL SWITCHBOARD
LOCAL SUBSCRIBER
TRANSMITTER CONTROL
RADIO TRANSMITTER
AMPLIFIER
SENDING SIGNAL UNIT
TO JACK
TRANSMITTER CONTROL
VANCOUVER
TO REC. SWITCH
RADIO RECEIVER
LOCAL OR DISTANT SUBSCRIBER
TOLL SWITCHBOARD
HYBRID COIL
NETWORK
TO JACK
AMPLIFIER
RADIO TRANSMITTER
TRANSMITTER CONTROL
- NOTE -
SIGNALING EQUIPMENT AT VANCOUVER AND OCEAN FALLS NOT SHOWN
OCEAN FALLS
SPECIAL FOUR-WIRE CIRCUIT IN PACIFIC MILLS HEAD OFFICE
TO REC. SWITCH
RADIO RECEIVER
SWITCHING KEY
TRANS.
CONTROL TO JACK
NETWORK
HYBRID COIL
TOLL SWITCHBOARD
LOCAL SUBSCRIBER
TRANS. CONTROL
RADIO TRANSMITTER
AMPLIFIER

Fig. 6—Simplified Diagram Showing Equipment at Vancouver, Campbell River, Ocean Falls and Prince Rupert

The Ocean Falls-Campbell River 210-mile radio link was finally cut into service April 1st, 1931, operating on 4,505 and 4,865 kilocycles respectively. Tests had been conducted on the basis of day and night service with the consequent changing of wave lengths. The night antenna was placed at the top of one hundred and fifty foot poles with the day antenna on the same poles approximately one-quarter wave length above ground. It was found that the amount of business received at night did not justify this change, so initial operation was carried on between the hours of 8 a. m. and 6 p. m. In the winter season the day frequencies are usually not effective after 6 p. m.

During the summer months it was possible to obtain fairly consistent twenty-four hour service on the day frequencies, calls being completed as late as 11 p. m. and as early as 4 a. m.

The Ocean Falls-Campbell River radiotelephone circuit has been in commercial operation for over a year and during this period results have been well above expectations. With few exceptions all business offered was completed, including calls to all parts of the United States and Canada, with as many as forty handled in a single day. The exceptions mentioned were due to land line failures on Vancouver Island, and to severe atmospheric conditions. These atmospheric storms occur about twice a year. During the first day of these phenomena signals are missing entirely, or are so weak as to be useless. Changing wave lengths over a wide range of frequencies does not improve matters. Usually at some period of the day the circuit will be normal long enough to complete any business that is waiting. For several days following, sometimes for a week, the circuit will be extremely erratic, with signals fluctuating over a wide range.

Fig. 5 shows, graphically, operation during the month of September 1931. It will be noted that three different frequencies were used in transmission to Ocean Falls. At this time tests were being conducted on 4,000 kilocycles and 5,400 kilocycles, as well as on the usual 4,865 kilocycles, to determine the optimum frequency for transmission at this time of year. Transient conditions such as fast, slow or selective fading with accompanying distortion are experienced at times, but it is surprising how little this affects a telephone conversation, particularly if the principals involved are experienced in the use of the telephone. Static is very rarely experienced in day operation. The Pacific Mills operating the pulp and paper plant at Ocean Falls transact considerable business by telephone to their head offices in Vancouver and San Francisco. At least one call of not less than twelve minutes duration, and usually close to a half-hour, is placed each day to Vancouver. Since the commencement of service these calls have all been completed with the exception of two occasions when land line failures were experienced.

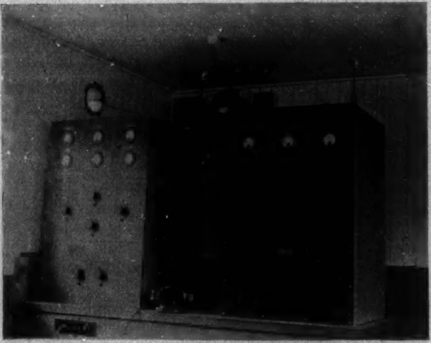

FIG. 7—PRINCE RUPERT TRANSMITTER INSTALLATION

In the early stages lack of secrecy was thought to be a serious obstacle, but up to the present no unfavorable reaction has resulted. At some future date it is planned to add secrecy equipment which is now under development for this type of installation. It will be noted from the simplified diagram, Fig. 6, that it is possible to operate the Ocean Falls terminal either with the usual hybrid termination or by straight four-wire. There are advantages in the use of four-wire operation from a secrecy standpoint but the particular advantage is in instances when signals are weak or erratic.

A further addition to the radio network occurred on January 15th last, when the City of Prince Rupert, British Columbia, was connected.

The radio equipment employed and the arrangement is essentially the same as Ocean Falls. Connection is made with Campbell River operating on the same wave length as Ocean Falls. This method of operation is desirable from an economic standpoint until such time as increased business justifies a separate circuit. The local telephone system is owned by the City of Prince Rupert and the radio circuit is terminated on its switchboard. Operating and maintenance is carried out by its regular telephone personnel.

A brief description of the operating procedure is as follows: On receiving a long distance call from a local telephone, the Prince Rupert long distance operator plugs into a jack designated "radio," which automatically starts the transmitter. A delay of seven seconds is required for the tubes to reach a temperature that will allow the safe application of high tension voltage. A red lamp appears in front of the operator when the transmitter is in readiness to receive a call. She then operates a ringing key which actuates a standard telephone ringer of the same type as used on composited telephone lines, thus modulating the transmitter with 135-cycle current. This signal is detected by the Campbell River receiver and operates the tuned 135-cycle portion of the Campbell River ringer, thereby producing an audible signal. The Campbell River operator answers by starting up her transmitter. As it will be remembered that commercial power is not available at Campbell River, the insertion of the plug in the switchboard jack first of all starts the gas-engine-driven alternator, which in turn energizes the transmitter. This added operation increases the interval before the transmitter is on the air by an additional ten seconds. The Campbell River operator then takes the particulars of the call and both transmitters are left running until the call is completed or until the Prince Rupert subscriber receives a report on his call. A call originating in Vancouver would be put through in the same manner by the Campbell River operator.

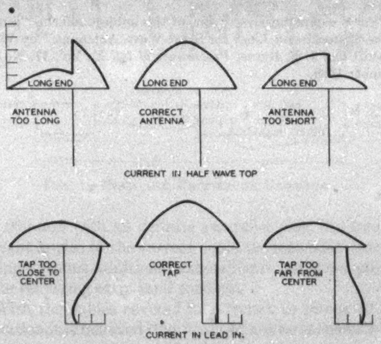

FIG. 8—ANTENNA DIAGRAMS SHOWING THE EFFECT OF VARIOUS ADJUSTMENTS ON THE CURRENT DISTRIBUTION

Although the transmitters at each station run only when business is being carried on over the circuits, the heaters on the quartz crystal frequency controls are on continuously to insure the frequency stability of the transmitters. The receiver, of course, is left on during the hours of operation, and is turned on and off as required by the regular long distance operator from her switchboard position.

To date, operating results experienced on the Prince Rupert circuit have been very good.

Considerable care is exercised in the construction and adjustment of the antenna systems. In all cases a horizontal half-wave Hertz antenna is employed, located approximately one-quarter wave length above ground, and connected to the equipment by a single wire transmission line. Care is taken to terminate the feeder in its characteristic impedance to preclude radiation from the feeder itself. A device consisting of a radio-frequency meter mounted in such a manner as to permit it being readily moved along the flat top or transmission line is used to explore the antenna. Readings are taken throughout the flat top and feeder by the aid of field glasses or a transit and the results plotted. Fig. 8 illustrates the effect of various adjustments.*

This type of antenna has been found to be somewhat directional, and consequently, is placed to take advantage of this directivity. The ground system consists of a network of buried copper wires.

Recently the Lulu Island location has again come into prominence with the placing of a 400-watt transmitter and subsidiary equipment. Tests are progressing with the aim in view of serving certain of the logging operations, canneries and like industries that are scattered along the coast and isolated in many ways, including communication. The connection with mobile stations such as ships or small harbor craft is another possibility. It is very likely that Ocean Falls in the near future will be operated direct to Lulu Island as considerably improved operation is possible for this distance as compared to Campbell River.

There is the probability that some of the cities in Alaska will be tied into the British Columbia network until such time as business justifies a direct circuit to the United States.

In concluding, it will be noted that the radio projects described are all of an experimental nature. Consistent with economy, it is felt that future work including additions to the present circuits will be of a more permanent nature.

Recent improved apparatus developed by the Bell Telephone Laboratories for harbor craft operation and related equipment embracing such features as secrecy, improvements in signaling, voice controlled relays, and the possible use of directional antenna systems, will provide additional means for improving service. The extent of the downward revision in radio equipment costs and the availability of suitable radio channels will govern the degree of expansion in the providing of radiotelephone service to the smaller communities of of the north. Touching on wavelengths, the cooperation of the Department of Marine of the Canadian Government has been of considerable assistance in the experimental work outlined and is worthy of special mention.

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*For a comprehensive review of this subject refer to "Single-Wire Transmission Lines for Short-Wave Antennas," by W. L. Everitt and J. F. Byrne, *Proceedings of I.R.E.*, Vol. 17, No. 10, October 1929.

# 115-Kv. Submarine Cable Crossing of the Columbia River

BY E. F. PEARSON,* Member, A.I.E.E. G. B. SHANKLIN,† Member, A.I.E.E. W. R. BULLARD,‡ Member, A.I.E.E. and S. B. CLARK* Non-member

DELIVERY of electric energy from the new Ariel Plant of the Inland Power & Light Company on the Lewis River, Washington, to the load center of the Northwestern Electric Company in Portland, Oregon, made necessary the construction of approximately 36 miles of transmission line including a 115-kv. submarine cable circuit crossing the Columbia River. The crossing site is just north of Portland city limits and about one mile west of Vancouver, Washington. The river, one of North America's largest streams, forms the boundary between the states of Oregon and Washington.

At the crossing location, the river is divided by the one-half mile wide Hayden Island, into two channels, the north channel being 3,460 feet in width and the south channel 1,360 feet. Two separate crossings, one across either channel, were therefore required. (See Fig. 1.) These were connected by an H-frame wood pole type transmission line as study had shown this to be more economical than to continue the cable across the island underground.

The selection of 110 kv. (nominal) for the transmission voltage was determined by an economic analysis of costs at various voltages for delivering energy from Ariel and other possible adjacent developments to load centers in the Portland area; also from consideration of interconnected operation with other utilities in the Northwest. This later consideration had a very important bearing upon the problem since all of the other major companies are now operating or contemplate conversion of principal trunk lines to nominal 110-kv. operation. Furthermore, physical interconnections already exist between all of these companies and interconnected operation has been employed for several years past, so the economic advantages to be gained and necessity for planning to meet the increasing demands for interchange capacity have been clearly demonstrated.

Cost comparisons between crossing the river overhead or submarine for the construction program necessary to meet the load and service requirements clearly established the economy of the submarine method. Factors contributing to this result were: the 198-ft. minimum clearance above low water requirement; the flat terrain at the crossing site or anywhere in the vicinity; the small increment cost for a double circuit overhead crossing over a single circuit making construction for two circuits the logical procedure although only one was needed initially; and, the unusual mechanical strength requirements for the overhead construction on account of the occasional very severe ice loading conditions experienced.

Very careful and thorough consideration was given to the idea of trenching of cables in the river bottom in order to provide protection from ship anchors and other forms of external damage. With present river depth at elevation minus 28 ft. (low water at 0) it was decided that the trench would have to be excavated to elevation minus 40 ft. in order to be beneath future ship channel bed as well as out of reach of projecting anchor and dredge cutter heads. Such a trench constructed 7 feet wide on the bottom with walls of 1:3 slope for withstanding river current would cost from $40,000 to $50,000 and with no definite assurance that the trench at right angles to the current could be kept open during laying without additional expenditures for sheet piling or for removing extra sand yardage.

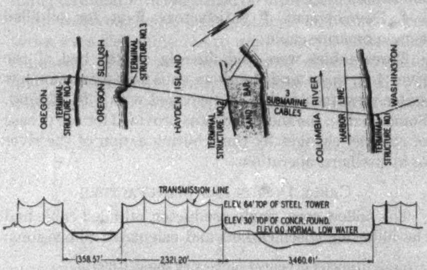

FIG. 1—PLAN AND PROFILE OF CROSSING

With the cables covered in a trench to minus 40 ft. elevation it is believed that it would not be economically practical to salvage the cable in case defects developed. This fact would therefore necessitate the abandonment of that cable and the writing off of a comparatively large investment. With oil-filled cable laid directly on the bed of the river it is believed that the cable can be readily lifted and repaired in case of fault developing. The Northwestern Electric Company has an experience record of 92 submarine cable years covering 11 three-phase 11,000-volt submarine cables laid directly on the beds of the Columbia and Willamette Rivers in the general vicinity of the new crossing. This experience record, excluding pothead failures, discloses only one failure. In that case failure occurred when cable was accidentally picked up by a sand digger clam shell. This favorable experience record, combined with greater accessibility and less chance of abandonment, together with fixed charge savings of from $5,200 to $6,500 per year were responsible for the decision to lay the cable directly on the bed of the river.

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*Northwestern Electric Company.

†General Electric Company.

‡Electric Bond and Share Company.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

During the three years study of this problem considerable time was devoted to consideration of the relative merits of cable with solid type of insulation *versus* oil-filled type. The experience and advice of high-voltage cable specialists in several manufacturing and utility organizations throughout the United States was sought and their help is gratefully acknowledged. Final decision to specify oil-filled cable was based on the following facts:

1. Most favorable operating records of oil-filled cable over the past four years, particularly when compared with solid type cable operating at high voltage.
2. High electrical endurance strength of oil-filled cable as demonstrated in laboratory and field tests.
3. Ability of the latter type of cable to maintain perfect impregnation and prevent void formation and ionization.
4. Development of satisfactory joint for oil-filled type submarine cable.

Three cables were laid directly on the bed of the river 4 ft. apart and the shore ends above extreme low water were trenched in and covered with 4 ft. of sand. Some slack in the shore ends was provided for use in case of channel changes by the scouring action of the river or by dredging operations.

### Cable Design and Manufacture

The hollow core, single-conductor, oil-filled cable had the following specifications and calculated dimensions:

Inside diameter of copper supporting spiral, 0.690 in.
Inside diameter of conductor strands, 0.790 in.
Outside diameter of conductor strands, 1.277 in.
Conductor cross section, 750,000 cir. mils.
Thickness of wood pulp paper insulation, 0.560 in. (nominal).
Perforated copper shielding tape (0.005 in.) interlocked with one paper tape.
Inside diameter of lead sheath, 2.497 in.
Outside diameter of lead sheath, 2.810 in.
Lead sheath 5/32-in. 2 per cent tin-lead alloy.
Two layers 16 three-ply tarred jute and asphalt.
Hard drawn copper wire armor (0.238 in. diameter).
One layer 16 three-ply tarred jute, asphalt and whiting.
Overall diameter, 3.80 in.
Weight, 20 lb. per ft.
Voltage rating, 115 kv., three-phase, grounded neutral.

Seven reel lengths were manufactured and each length included not only the amount required for installation but also additional cable for test purposes. As manufactured, three lengths were approximately 3,780 ft. each, three more were approximately 1,600 ft. and the remaining 832-ft. length was shipped on a separate reel, to be held in reserve for possible future emergency repair work.

The lead sheath was applied before drying and impregnation treatment. Each length was placed in a steam chamber. Vacuum was applied at each end of the hollow core and drying continued until all moisture was removed. Due to the long lengths involved this drying treatment was necessarily slow, the 3,780-ft. lengths requiring 391 hours. After drying, impregnation was completed with carefully selected, degasified oil having the following characteristics:

Specific gravity, 0.91.
Viscosity at 37.8 deg. cent., 100 (Saybolt).
Pour point, −40 deg. cent.

Following the usual practise the oil in the core, after impregnation was completed, was continuously maintained under positive pressure by use of one or more cell type pressure reservoir units connected to cable end. The first principle of oil-filled cable practise is always to maintain positive oil pressure at all points of cable length in the factory and during shipment, installation and operation. The various operations that are closely followed throughout are solely for the purpose of initially removing air, moisture and other impurities from the entire system, completely filling with oil and maintaining positive oil pressure, so that additional impurities cannot enter through accidental leaks.

After impregnation the cable lengths were subjected to a special volumetric pressure test for assurance that all air and other gases had been removed. The complete lengths (or test samples cut from the ends) were then subjected to various special and standard acceptance tests, chief among which were the following:

1. Factory reel high potential test 166,000 volts, conductor to sheath for 15 min. (60 cycles), before armoring.

2. Dielectric power factor and ionization factor, 20 to 100 volts per mil, 60 cycles, each reel length before and after armoring. Ionization factor limit 0.2 per cent, actual 0 per cent.

3. High-voltage time test. Three 75-ft. lengths, one before and two after armoring. 196,000 volts for 6 hours with 20 per cent voltage steps every 6 hours to failure.

The samples failed at 235 kv. in two, three and five hours.

4. Two 25-ft. samples before armoring for 60-cycle dielectric loss test.

The average measured power factor was: 0.32 per cent at room temperature, 0.27 per cent at 60 deg. cent., 0.28 per cent at 70 deg. cent. and 0.30 per cent at 80 deg. cent.

5. Three 15-ft. samples, two before and one after armoring for bending test.

Four cycles of 180 degree bending at −10 deg. cent. around a mandril 12 times cable diameter. Physical condition noted but electrical tests omitted as meaningless.

After test the seven shipping lengths were as follows: three lengths 3,717 ft. each, three 1,532 ft. each, and one spare 832 ft. length. Each was placed on a separate reel in the body of which was mounted a sufficient number of cell type pressure reservoir units to maintain an oil pressure between 5.0 lb. and 15.0 lb. during shipment and installation. All shipping reel bodies were 7 ft. 2 in. wide. The three reels for 3,717 ft. lengths were 11 ft. 2 in. in diameter and the remaining four had a diameter of 9 ft. 6 in. Each reel was axially mounted in a permanent cradle with band brakes for unreeling cable. Due to excessive size and shipping weight, 45¾ tons for 3,717-ft. units and 21½ tons for 1,532-ft. units, it was necessary to use special gondola freight cars and load only one reel per car. Obviously, such excessive size and weight required special manufacturing facilities throughout and the various operations presented a very interesting and difficult problem.

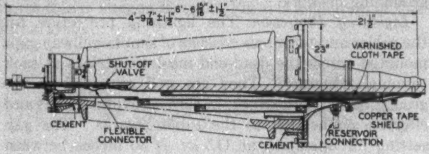

Fig. 2—Details of 132-Kv. Terminal for Oil-Filled Cable

*Carrying Capacity of Cable.* The carrying capacity of a submarine cable, where the same size conductor is used throughout, is determined by the thermal conditions at the shore ends, the temperature rise of immersed section being, of course, much less. The carrying capacity of this particular installation was more difficult to determine than usual because of the relatively short vertical risers at the ends representing the limiting thermal conditions. Due to transfer of heat from these exposed vertical risers into the earth the usual formulas for cable in air do not exactly apply and the thermal correction factor was checked by heat run after installation. On the basis of an ambient air temperature of 40.5 deg. cent., this cable has a conservative rating of 575 amperes for maximum conductor temperature of 70 deg. cent. at vertical risers and with copper armor bonded at base of terminals.

If steel armor had been used under the same conditions, the rating would have been only 430 amperes, due to excessive armor and sheath losses. The advantages of low resistance copper armor in this respect are fully described in a previous publication.[1]

## Accessory Design and Manufacture

The following accessories and special installation and maintenance treating equipment were also furnished:

*Accessories*

Fourteen single-conductor, outdoor porcelain terminals or potheads.

Six 6-gallon type CC (gravity cell type) oil feeding reservoirs.

Eight 10-gallon type CC reservoirs.

Four 10-gallon type AC (cell type) oil pressure reservoirs for maintaining pressure on emergency oil supply tanks at each terminal.

Eight 50-gallon emergency oil supply tanks with oil level gages, nitrogen gas cylinders, valves, fittings, etc., connected two in parallel at each terminal.

Eight hundred gallons special oil in 50-gallon drums for filling terminal equipment after assembly.

Four valve panels (six valves each) for emergency parallelling or interchange of oil feed for each phase.

Two repair joints with Everdur armor box and clamping rings.

Copper tubing, armored lead piping, valves and miscellaneous fittings for connecting oil system.

*Treating Equipment*

One portable, motor-driven oil degasifier.

One portable, motor-driven vacuum pump.

One impregnating bottle.

Rubber vacuum hose, toggle clamps, tanks of specially dried carbon dioxide and miscellaneous fittings.

The outdoor potheads were rated at 132 kv., following the usual practise of using one size larger porcelain. A cross-sectional drawing of this design is shown in Fig. 2. The guaranteed dry and wet 60-cycle flashover was 375 kv. and 280 kv. respectively and before shipment the potheads were subjected to the following test for leakage: 4 hr. vacuum followed by 2 hr. oil pressure at 80 deg. cent. The terminal lugs had a flexible type stud to allow limited movement of cable conductor during expansion and contraction. There was also a special shut-off valve in the stud so that oil pressure could be maintained in cable core while vacuum treating and filling terminal with degasified oil after assembly.

All reservoir units, piping fittings and other accessories were also subjected to rigid tests for leaks before shipment. They were again tested after installation and then carefully dried, evacuated and filled with degasified oil. The cell type reservoir designs have been described in detail in previous publications.[2,3] One of these[2] also gives a general outline of the principles of oil-filled cable practise and a complete bibliography.

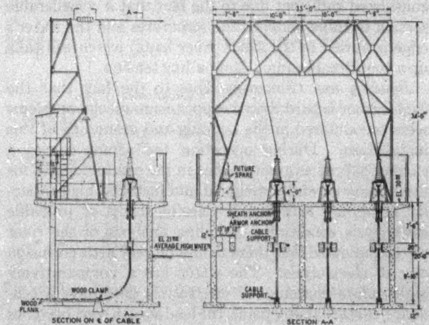

Fig. 3—Outline of Design for Terminal Structures

## Design of Field Installation

*Terminal Structures.* The terminal structures, four in number, consist of reinforced concrete bases and platforms supporting cable terminals and accessories and steel dead-end structures for the overhead lines. (See Fig. 3.) The decks of these four structures are all at the same elevation and are above the usual high water level, but the lower portions will be submerged at high water. The deck of each structure is surrounded by a barrier of steel plate to protect the potheads and accessories from bullets of youthful sportsmen who frequent the neighborhood, and facing the water is a large sign warning against anchorage.

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[1] For references see Bibliography.

The structure on the Washington side of the main channel has a foundation of wooden piles. This structure is nearer to the water's edge than the others and is adjacent to the ship channel. No piles are used underneath the other structures. Jetties or dykes for protection against undercutting and damage by floating objects during flood periods will be provided for the structures on both sides of the main river channel when deemed necessary.

The steel dead-end overhead structures are mounted on the decks of the concrete terminal structures. They are self-supporting and are designed to withstand maximum expected strain, under heavy ice loading of the 795,000-cir. mil A.C.S.R. overhead conductors. To guard against failure from unforeseen loading conditions each conductor is dead-ended through a shearpin designed to fail at the value corresponding to the maximum safe strain on the structure.

*Anchoring.* Anchoring of the cables is accomplished by the use of two concrete dead-men at each terminal structure. Chains are carried back from these dead-men to the three cables. Attachment to the cables is made by means of basket grips, this attachment being considered sufficient due to the fact that a considerable section of cable between the structures and the water's edge is buried in the sandy river bank, which will take up a considerable amount of pulling tension.

*Bonding and Grounding.* Due to the fact that the cable armor is hard drawn copper some special problems were encountered in the bonding and grounding of this installation. During operation the armor carries a current almost as great as that in the conductor and for this reason carefully designed and installed high capacity bonds are necessary. Careful study of probable electrolysis conditions, including analysis of the river water, indicated that there should be very little corrosion due to electrolysis. The water has a comparatively high sulfate content. If electrolysis does have a tendency to start at any point, the lead sheath soon becomes coated with a tough, permanent film of lead sulfate, thus automatically stopping the action. However, since with copper armor any corrosion which might occur would affect the anodic lead sheath and not the armor, it was considered advisable to take all possible precautions against damage by corrosion. To this end the armor strands of the three cables are bonded together separately from the sheaths, the latter also being bonded together separately and grounded. The two sets of bonds are connected together by a removable jumper, both armor and sheath being grounded when this jumper is in place. The idea of this arrangement is to permit periodically inserting an ammeter between the armor and sheath and testing for electrolysis currents. If appreciable currents should develop the sheath and the armor can then be separated by removing the jumper or they can be connected through a battery supplying a potential counter to the electrolysis potential.

Arrangement of the grounding system is shown in Fig. 4. The ground electrodes consist of a series of driven rods interconnected with each other and with all equipment and structures, forming a low resistance grounding network.

*Lightning Protection.* The lightning protection for the cables and terminals consists of simple spillway gaps mounted across the dead-end insulator strings at each terminal structure. They are well grounded to the grounding network which, in turn, provides a short and effective connection to the cable sheaths. The gap setting for operation at 115 kv. is 30 inches between points, this being considerably below the impulse insulation strength of the cable and terminals and also somewhat below the maximum recommended setting of 36 inches given by the manufacturer of the cable and accessories. It is also somewhat higher than the maximum expected switching surge voltages, so lightning should be the only cause for flashover. Flashover of these gaps may involve a tripout of the transmission circuit in a similar manner to a lightning stroke occurring at any other point of the line.

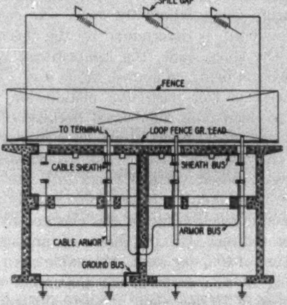

Fig. 4—Bonding and Grounding Arrangements at Terminal Structures

On account of the fog and contamination condition existing along the river, a leakage distance of 80 inches, equivalent to 1.2 inches per kv. to ground, is provided on the terminal bushings. Two strings in yoke each of seven suspension units giving leakage distance of approximately 90 inches are used on the dead ends. No pedestal insulators are required with the simple structure design employed.

*Oil Level Alarm System.* Since the installation is somewhat remote from the nearest attended substation it was considered advisable to provide remote indication of oil level conditions in the oil reservoirs. Such indication is provided by alarm devices at the oil reservoirs, which devices are connected to telephone lines terminating in Vancouver Substation. By a system of resistances, individual indication of the different reservoirs from a given location can be given over a single telephone line, the indications being obtained by an ammeter type of indicator in the station. Only three of the structures are equipped with this signal system, namely the two on the main channel and the one on the north side of Oregon Slough. Fig. 5 is a diagram of this signal system.

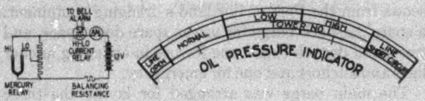
TO BELL ALARM
HI
LO
HI-LO CURRENT RELAY
12V
MERCURY RELAY
BALANCING RESISTANCE
LINE OPEN
NORMAL
LOW
TOWER NO
HIGH
LINE SHORT CIRCUIT
OIL PRESSURE INDICATOR

FIG. 5—OIL PRESSURE SIGNAL SYSTEM

*Emergency Oil Supply.* Since in case of damage to the cable, resulting in an oil leak, as for instance by ship's anchor, considerable time must elapse before the cable can be raised and the damage repaired, it was considered advisable to provide emergency oil storage so that continuous oil flow can be maintained until repairs can be effected. This emergency storage consists of simple drum type reservoirs, two of 50-gallon capacity each for each terminal structure, with suitable piping and valve arrangement to connect these reservoirs with the cable oil system when needed. The valves are hand operated. These reservoirs are provided with tanks of nitrogen under pressure not normally in contact with oil, but with valve arrangements by which the oil in the tanks can be displaced by the nitrogen under emergency conditions. The contact of nitrogen with the oil for short periods of time is not considered especially objectionable, although contact for longer periods of time would be definitely deleterious. The nitrogen is supplied in ordinary high pressure cylinders fitted with special reducing valves. Safety valves are provided to limit the pressure of the oil when forced by the nitrogen gas from the emergency tanks to the cable oil system. The nitrogen is required to be extra dry and the cylinders are required to be dried out before the nitrogen is introduced. Since it is necessary to avoid contact of the oil in the emergency tanks with air at all times during normal operation these tanks are serviced by small auxiliary reservoirs of the expansible cell type which maintain positive oil pressure in the main tanks at all times. See Fig. 6.

### OIL PRESSURE AND FLOW CHARACTERISTICS

During installation great care was taken to maintain positive oil pressure at all times as a safeguard against accidental leakage and also during periods when cable ends were opened for terminal assembly. Under these conditions a predetermined value of oil flow must be maintained, just sufficient to prevent entrance of moisture or air. During operation the same problem exists and, in the case of submarine cable, the surrounding water pressure at different points of the profile must be considered.

Submarine cable in long lengths presents a more difficult oil feed problem than ordinary underground cable. The limiting conditions are, maintenance of positive oil pressure at middle of cable length during coldest winter weather, without exceeding a safe oil pressure on sheath at low water level under full load summer conditions. The armor gives some support to sheath and the practise is never to exceed a pressure of 20 lb. per square inch at low water level. Water is more dense than oil. There is, approximately, one pound gain in head pressure of water for every 30 ft. of depth, as compared with oil. The head pressure of oil is approximately 2½ ft. per lb.

The Columbia River crossing was particularly difficult because of the great difference (33 ft.) between low and high water levels. The maximum depth in middle of channel at low water level is 30 ft., giving a depth of 66 ft. at high water. After a careful study of conditions it was decided to use gravity feed (type CC) reservoirs mounted at the same level (44 ft. above low water) at both ends and feeding towards middle of cable length. This represented an oil pressure of 18 lb. per square inch on sheath at low water level and left only one or two pounds margin of oil pressure over water pressure at middle of length when load is dropped in the winter at high water level. The margin is sufficient, however, since the assumed conditions are extreme and of only transient nature, pressure drop in cable core lasting for less than an hour after load is dropped.

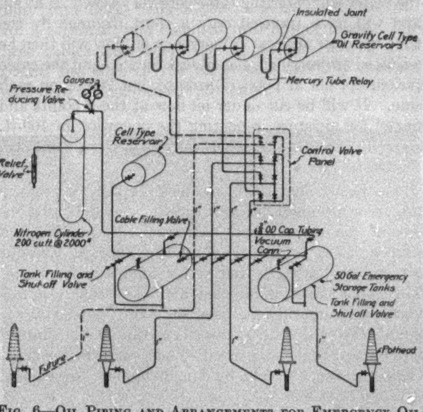
Insulated Joint
Gravity Cell Type Oil Reservoirs
Mercury Tube Relay
Gauges
Pressure Reducing Valve
Relief Valve
Cell Type Reservoir
Control Valve Panel
1"
Cable Filling Valve
Nitrogen Cylinder 200 cu.ft. @ 2000#
3/8" OD Cop. Tubing
Vacuum Conn.
Tank Filling and Shut-off Valve
50 Gal Emergency Storage Tanks
Tank Filling and Shut off Valve
Future
Pothead

FIG. 6—OIL PIPING AND ARRANGEMENTS FOR EMERGENCY OIL SUPPLY

These limiting conditions, and the need of utilizing all available oil pressure, did not allow the use of restrictors for limiting oil flow in hot weather in case of accident. In the winter such restriction is not needed but in the summer the reservoirs would empty at a fairly rapid rate in case of a "full open" accidental leak in the system.

This question was given careful study. Space does not allow inclusion of details. Briefly summarized the conclusions are:

1. The regular switch signal or the oil level alarm relays will give warning immediately or soon after the accident, allowing an emergency crew to be on the scene within one or two hours.

2. The position of the failure, and other factors, will determine whether the reservoirs involved are exhausted of oil by that time. If not, the emergency oil supply is turned on and the nitrogen gas pressure adjusted (20 lb. limit) to maintain an oil flow not greater than 6 gallons per hr. This will entirely prevent entrance of water or air in the system and the flow can be maintained until the damage is located and repaired.

3. Even if one or more reservoirs is found exhausted the water will enter the cable core very slowly, if at all, and will have traveled only a short distance by the time the crew arrives. Emergency oil flow will then be adjusted as described, the oil leak located and the cable picked up, not at point of leakage, but 200 ft. on each side. It will be cut under oil flow at these points and tested for moisture, repeating the operation in 100-ft. steps if necessary. A length of replacement cable will then be spliced in.

The repair joints, held in stock for such emergency use are of standard design successfully used in previous conduit installations with the exception that the spun copper casing is protected by a cylindrical Everdur armor box, having bolted armor clamps at each end. The cable paper is stepped and the usual low loss varnished cambric tape used for reinforcement wrappings. The halved connector is of the double shut-off plug design that has proved so successful in the past. Copper casing, 3 ft. 8 in. by 6 in. diameter. Armor box, 4 ft. 2½ in. by 8 in.

## INSTALLATION

The importance of this installation, the unusually great size of the reels of cable, and the fact that this was the first submarine installation of oil-filled cable to be made in this country, set a task of a new order for the construction forces, and created many unusual construction problems.

Several weeks before the installation was started, a school was set up for the construction personnel and intensive training was carried out. This included such work as making up pothead connections by the use of short lengths of scrap cable, etc. It was undoubtedly this training together with very careful engineering of the construction work that enabled the installation to be made without serious mishap.

Equipment suitable for laying the long heavy lengths of submarine cable was difficult to assemble from a harbor the size of Portland's, and it was only after considerable effort that necessary equipment at a reasonable rental cost was obtained. This equipment as finally assembled consisted of a flat-decked barge, 400-ton capacity, 125 ft. long, 32 ft. wide, on which the three cable reels for each crossing and control equipment were placed. As auxiliary to the cable barge, a steam dipper dredge barge was utilized as a derrick, and in addition there were two small gasoline donkey scows from the Port of Portland's dredging equipment, a spare flat-deck barge for use as spare deck space, and two small derrick tugs—one for use in changing anchor lines and anchors and one for emergency.

The main barge was arranged for laying the three cables at each crossing simultaneously, the reels being mounted in tandem for proper deck load distribution. The two reels nearest the laying end, or stern of the barge, were raised sufficiently to allow the cable from the reel forward to pass underneath. Easy running rollers were placed at such points as to eliminate all possible friction. An overhanging timber structure was constructed at the stern of the main barge, with rollers arranged for a minimum safe bending radii of cable as it was fed overboard, and which spaced the cables 4 ft. apart. The two flanges of each reel were equipped with friction band brakes, one used for laying control and one for emergency.

FIG. 7—AEROPLANE VIEW OF EQUIPMENT DURING LAYING OF CABLE

Calculations for running lines and strains were made on the basis of maintaining the main barge when laying the cable sidewise to river current, which at the time of laying was approximately seven miles per hour. A donkey scow was placed at bow and stern on the upstream side of the cable barge. Two steel lines with large anchors attached from each of the donkey scows were maintained upstream while laying and moved in successive steps across the river. The derrick barge was held alongside the main barge on the downstream side, with steel lines from the donkey drums, also with anchors attached, from bow and stern for control of movement across the river. These anchors were also moved as required. The derrick tugs mentioned above were used for changing anchors and to clear lines of driftwood, trees, etc., which were quite heavy at this flood stage of the river. A view of the general arrangement as described above is quite clearly shown in Fig. 7, and the same arrangement is shown diagrammatically in Fig. 8.

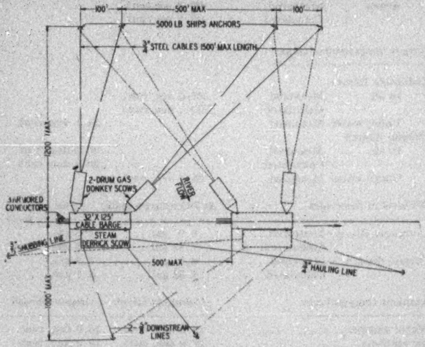

Fig. 8—Diagram of Arrangement of Equipment For Laying Cable

Buzzer and bell signals were provided to each operation control point. One control was from the point where the cable went overboard, controlling slack and reel movement; another point controlled the barge movement across the river and the upstream anchor lines from the donkey scows. This control point was in turn controlled by telephone from the shore where men with transits were located for alinement of the cable across the river.

The shorter sections of cable across the Oregon Slough were laid first, and on a rapidly rising river. For plan of crossing, see Fig. 9. The three shore ends, one at a time, were pulled over rollers, located at frequent intervals, into No. 4 terminal structure by means of lines from derrick hoisting drums, fastened to the armor pulling eyes at the cable ends. (The terminal structures are numbered consecutively from 1 to 4, beginning with the one farthest north.) Cables were then clamped in final position, with necessary slack above terminal pedestals for terminal installation.

Temporary oil connections were made between the three cable ends and the three permanent oil pipings which had been installed with permanent oil reservoirs, emergency oil tanks, etc., previous to cable laying operations. Oil supply to the cable was then made from the permanent oil supply apparatus; oil supply to the cable from the temporary pressure reservoirs shipped with the reels being closed off. Reserve supply of oil and the degasifying equipment were connected and made ready to provide against any possible emergency that might arise. After all connections were complete, short slacks were laid just outside terminal No. 4 and temporarily anchored, and the laying of the Oregon Slough crossing started. This laying to a point approximately 300 ft. from terminal No. 3, where slack was to be dropped, took five hours. Slack, as engineered for this location, was laid out on the deck of the spare barge lashed in place to cross timbers which were later raised with derrick and the spare scow pulled from under the suspended cables. The suspended cables were then carefully lowered to the bottom of the river, later checked as to lay by a diver, and then the lashing cut, allowing timbers to float to surface of river. The laying equipment was then moved to terminal No. 3, the shore end footage of the cable pulled from the reels and placed in the shape of a figure eight on the deck of the spare barge. Reels were then removed from the main barge deck, ends of the three cables pulled into No. 3 terminal, and clamped into proper place. The three cables were then, one at a time, moved over toward the edge of the barge and carefully lowered overboard in final location alongside.

Fig. 9—Aeroplane View of Crossing

Laying of the three longer sections across the main channel was more difficult, on account of the extreme high water and heavy current, but was accomplished in the same manner as the Oregon Slough crossing. Laying of these lengths was started from structure No. 1 on the Washington side of the river and laid to terminal No. 2. The crossing time of the river proper was approximately fourteen hours, the following two days being used in disposing of slack at the outer edge of the

800-ft. sand-bar and working the barge equipment through the dredged channel to structure No. 2.

The same preparations were made at No. 1, where cable ends were first temporarily connected to the permanent oil reservoir system for any oil emergency condition, as were made at No. 4. These preparations were called into use shortly after the laying process started.

When about 1,000 ft. from structure No. 1, the oil pipe connection, between the inner end of the cable and the oil reservoirs contained within the reel body, was sheared off on account of creepage movement of the inner layers of cable. The man handling the emergency oil apparatus at structure No. 1, immediately noticed a drop in oil pressure and, as per instructions, supplied the emergency oil, maintaining the established pressure. Before the crossing of the main channel was complete, the oil connections on the two remaining cables were also sheared off, also owing to the slippage of the inner layers of cable on the reel drum. The leaks thus developed could not be closed off until sufficient cable was taken from the reels to allow access to the inner layer, and at one time it was problematical as to whether there was a sufficient supply of degasified oil available to maintain oil pressure on the cable until oil leakage from broken connections was stopped.

After the cable laying was completed, terminal pothead installation was immediately started at terminal No. 3, the necessary oil flow from cut cable ends being supplied from the permanent oil system through the temporary oil piping at terminal structure No. 4. No difficulty was experienced at any time during installation. The entire structure was temporarily covered with canvas to protect the working deck from rain and, in turn, each terminal location was enclosed with a special tent during taping and terminal assembling operations.

Terminals were next installed at terminal structure No. 4 with oil control for operations at this point through the cable from the permanent oil system at No. 3. The same procedure in rotation was followed for the terminal installation at structures Nos. 2 and 1. In all terminal assembly operations, as well as at other times, telephone communications were maintained between all four structures. This communication between structures allowed very close regulation of required oil flow and pressure during terminal installation and also for the final adjustment and testing of the entire oil system.

Aside from the broken oil connection, no difficulty of any serious nature was experienced during the entire installation of cable and terminals.

As soon as the installation was completed a three-phase, 60-cycle short-circuit current heat run was made, temperatures, induced sheath and armor currents, oil volume changes, etc., being carefully measured. This heat run served a two-fold purpose; it caused uniform dispersion and absorption of any small amounts of impurities that might not have been excluded and it furnished a final check on all theoretical calculations. Table I gives a summary of these calculations and the essential heat run data.

TABLE I—GIVING CALCULATED AND HEAT RUN DATA

| Circulating current (avg.)* | | | 840 ampere load | 795 ampere load |
|---|---|---|---|---|
| | Sheath | Measured | 12.1 per cent | |
| | | Calculated | 11.3 per cent | |
| | Armor | Measured | 90.3 per cent | |
| | | Calculated | 93.2 per cent | |
| Armor temperatures (max.) | | | | |
| Columbia River | | | | |
| | In air | Measured | 28.0 deg. cent. | |
| | | Calculated | 30.1 deg. cent. | |
| | Under water | Measured | | 24.1 deg. cent. |
| Oregon Slough | | | | |
| | In air | Measured | | 30.5 deg. cent. |
| | | Calculated | | 29.7 deg. cent. |
| | Under water | Measured | 25.4 deg. cent. | |
| Oil level in reservoirs | | | At 795 ampere load | At no load |
| Columbia River | | Measured | 8.0 gal | 4.5 gal. |
| | | Calculated | 7.88 gal | 4.2 gal. |
| Oregon Slough | | Measured | 4.8 gal | 2.8 gal. |
| | | Calculated | 4.53 gal | 3.1 gal. |
| Ambient temperatures | | | Columbia River | Oregon Slough |
| Water ambient | | | 15.0 deg. cent. | 16.0 deg. cent. |
| Air ambient | | | 17.0 deg. cent. | 18.0 deg. cent. |

*Percentages given are per cent of ampere load.

### OPERATION

Operation of the cable under normal operating conditions since June 19 to date has been very satisfactory. Cable temperatures and oil level fluctuations have followed the calculated values very closely with varying load conditions.

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1. *Losses in Armored Single Conductor Lead-Covered A-C. Cables*, by Schurig, Kuehni and Buller, TRANS. A.I.E.E., 1929, p. 417.

2. *Characteristics of Oil-Filled Cable*, by G. B. Shanklin and F. H. Buller, TRANS. A.I.E.E., 1931, p. 1411.

3. "Oil Pressure Reservoirs for Underground Cable, by T. C. Aitchison, *General Electric Review*, July, 1931.

## Discussion

**Robert J. Wiseman:** The paper brings out an interesting historical fact. It was not many years ago that transmission of power by cables at high voltages was not satisfactory and the utilities complained of limitations placed upon them. The last few years have seen a great change, starting with the single-conductor, 66-kv solid type submarine cable installed by the Philadelphia Electric Company at Wilmington, Delaware. When this Columbia River crossing was proposed and several manufacturers were asked for engineering advice, they did not hesitate to state that it was feasible for 66 kv as originally planned and later when the voltage was raised to 110 kv, again with the engineers of both the Electric Bond & Share Company and the

Northwestern Electric Company proposed an oil-filled type of cable. The writer's company did not hesitate to offer also as an alternate a solid type of cable, believing it practical for this installation.

These recent installations of long length, high-voltage cables should be a source of comfort and encouragement to the utilities in solving their future transmission problems. The cable manufacturers have not only overcome the limitations imposed upon transmission in the past, but also have eliminated the cable as the "neck in the bottle" of best design of a high-voltage, large power transmission system. The manufacturers have spent the time and money for engineering, research, and equipment to meet the utility needs.

Congratulations are due the company which manufactured the cable for this 115-kv installation for the carefulness and thoroughness with which it has carried out the engineering and manufacture; and also to the utility for its confidence in the feasibility of such an installation.

# Thermal Transients and Oil Demands in Cables

BY K. W. MILLER* and F. O. WOLLASTON†
Member, A.I.E.E. Associate, A.I.E.E

***Synopsis.***—*A simple method is given for the precise calculation of temperature variations in underground power cables due to sudden changes in loading. It is shown how the same method is employed for finding the oil demands of oil-filled cables under similar circumstances. A generalization is introduced which permits the temperature variations and oil demands of cables to be readily calculated for load variations of any sort whatever. A method of finding the pressure at any point in the cable insulation at any time is also outlined.*

*The simplified methods eliminate the necessity for a knowledge of higher mathematics and Bessel functions, which would be required in using the fundamental equations. Calculating charts and other devices permit complete solutions to be obtained in less than 20 per cent of the time formerly required.*

* * * * *

## INTRODUCTION

UNDERGROUND power cables almost always operate under variable loading but, because of mathematical difficulties, their temperatures and allowable carrying capacities are usually calculated on the basis of some more or less equivalent steady load. Such approximate methods have been found to be entirely inadequate in so many cases occurring in practise that a precise method has been developed for obtaining the exact temperature and its variation at any point in the cable which will occur at any time due to load changes of any sort whatever. Because the general thermal transient is so basic to all problems of cable rating on a temperature basis, as well as indispensable to a solution of oil flow problems in oil-filled cables, the broad importance and significance of this problem in the design and operation of all insulated power cables is apparent.

It is the purpose of this paper to present the solutions for three problems, namely (a) temperature and oil flow transients for abrupt load changes, (b) the same transients for any general load variation, and (c) radial distribution of oil pressure in the insulation during load changes of either of the preceding types. The completely general solutions of items (b) and (c) have not been published heretofore. Other articles have been published dealing with item (a)[1-4] part of (b),[6] and with longitudinal pressure drops in cable cores and oil feed pipes under various conditions[1-4] and pressure-volume characteristics of oil reservoirs.[1,4,5] Most of these topics are not repeated here. However, this paper presents some short-cut methods and charts by means of which the very complicated and laborious mathematics underlying all these problems have been reduced to a comparatively short application of simple arithmetic and makes the solution easily applicable to temperature problems in cables not of the oil-filled type.

The theory has been independently checked and also verified in every important detail (except for radial pressure drop) by field and laboratory tests which will be referred to from time to time. This being so, mathematical derivations will be relegated to the appendix and the essentials viewed in outline.

The basic assumptions made in the following work are:

1. The problem is initially or can be reduced to one of circular symmetry.
2. The cable conductor has thermal capacity but negligible thermal resistivity.
3. The insulation has both thermal capacity and resistivity.
4. The sheath has thermal capacity, negligible thermal resistivity in its metallic portions, but appreciable thermal resistivity from sheath surface to duct surface.
5. The dielectric power factor is uniform throughout the insulation, and the dielectric loss per unit volume varies as the square of the voltage gradient.
6. The above properties of the cable are constants, that is, they do not vary with temperature or radius.

Most of these assumptions are very nearly true for conditions encountered in practise and are justified by very close agreement between theory and test. Initially duct temperature $T_o$ is also assumed constant and, when this assumption is not justified, an empirical correction must be made.

The superposition principle is completely applicable both for loading (heat sources) and in time, and can be applied with great effect in the development and simplification of the problem. According to this principle, it is permissible to find the solution for unit change in copper, dielectric or sheath loss separately, and then build up the solution for any desired composite load change by proportioning the effects due to each loss and adding. It is also permissible to pass directly from the solution for one abrupt or rectangular load change to two or more successive changes by adding, with proper time sequence, the solution for each rectangular change independently computed. As a final consequence, it allows the Duhamel integral to be applied directly to the rectangular load change solution so that the equations for any general load variation whatever immediately follow almost by inspection.

## SOLUTION FOR RECTANGULAR LOAD CHANGE

The fundamental temperature equation for an abrupt change of load between constant, but different, initial and final loadings is:

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†Street Dept., Commonwealth Edison Company, Chicago, Ill.

1. For numbered references see Bibliography.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

$$T = \sum_{n=1}^{n=\infty} e^{-\lambda_n t} C_n F_o(u_n x, K_n) + \frac{W_c''p}{2\pi} \log R/x + \frac{W_i''p}{4\pi \log R/r}\left(\log\frac{R}{x}\right)\left(\log\frac{Rx}{r^2}\right) + (W_c'' + W_i'' + W_s'')E + T_o \qquad (10)$$

(For notation, see List of Symbols. For derivations and complete directions for enumerating all equations, see Appendixes I to IV.)

For conductor temperature, $x$ is replaced by $r$, and for sheath temperature by $R$. The component oil demands contributed by shrinkage of the conductor, sheath, and insulation are, respectively:

$$a_1 = (Cc/pq)\sum^{n} u_n^2 e^{-\lambda_n t} C_n F_o(u_n r, K_n) \qquad (18)$$

$$a_2 = (Vv/pq)\sum^{n} u_n^2 e^{-\lambda_n t} C_n F_o(u_n R, K_n) \qquad (19)$$

$$a_3 = (2\pi\epsilon/pq)\sum^{n} e^{-\lambda_n t} C_n [F_1(u_n R, K_n) - F_1(u_n r, K_n)] \qquad (20)$$

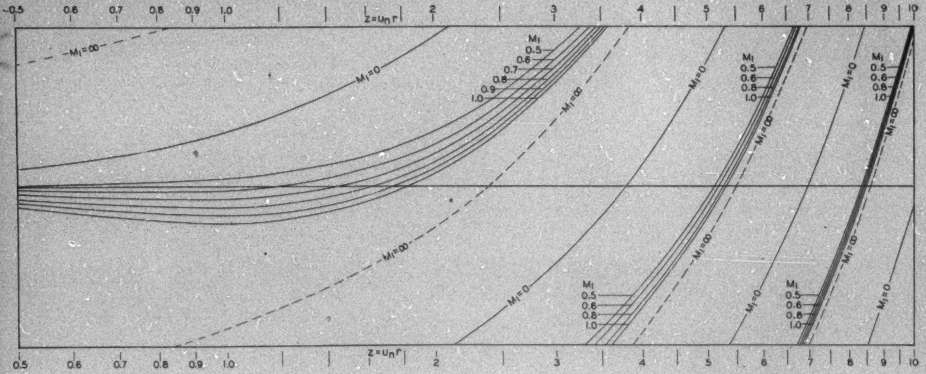


CHART 1

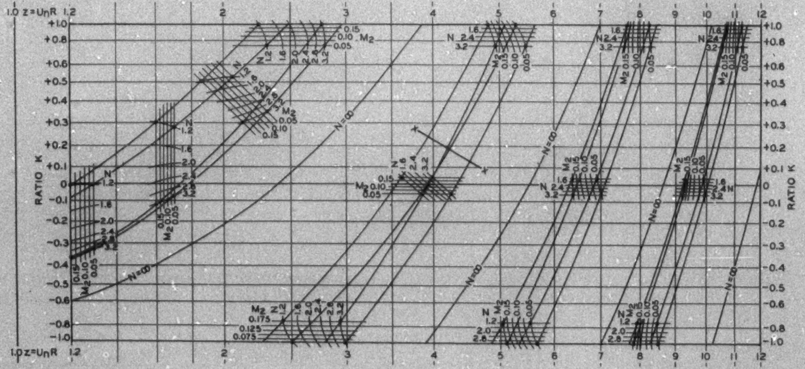


CHART 2

Instructions for Using Charts 1 and 2*

1. Lay Chart 2 over Chart 1 so that the $Z$ axes coincide, and $Z = R/r$ on Chart 2 coincides with $Z = 1$ on Chart 1
2. Interpolate on Chart 1 the sequence of curves for $M_1$, and interpolate on Chart 2 the sequence of curves for $M_2$, $N$
3. Note the points where intersections occur between the interpolated curves of Charts 1 and 2. Three intersections are sufficient
4. For the $n$ points of intersection, read off $K_n$ from the vertical scale. Also read off $Ru_n$ and $ru_n$ from the horizontal scales of Charts 2 and 1 respectively, starting at the left

*In printed copy where Chart 2 is not transparent or removal permitted, it is convenient to trace the $z$ axis, the interpolated $P$ curve for desired value of $M_1$, and sufficient identifying abscissas $z$, from Chart 1, on transparent paper, and to lay this tracing over Chart 2 with proper horizontal shift $R/r$ (to the right), after which intersections may be found as already described and the total oil demand is

$$a = (a_1 - a_2 + a_3)$$

In the foregoing equations, values of $u_n r$, $u_n R$, and $K_n$ are obtained from $n$ successive intersections (three are generally sufficient) of the curves of Charts 1 and 2, which are entered with values of $M_1 = Q_1/2\pi q r^2$, $M_2 = Q_2/2\pi q R^2$, $N = p/2\pi E$, and $R/r$. When $x$ is any radius other than $R$ or $r$, then $u_n x$ is obtained by calculation from $u_n R$ or $u_n r$, i. e., $u_n x = (u_n R)\,(x/R)$. The functions $F_o\,(u_n x, K_n)$ are obtained from Chart 3. The functions $F_1\,(u_n x, K_n)$ are obtained from Chart 4. Values of $C_n$ are obtained from the equation:

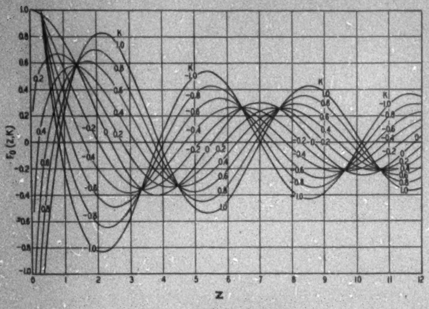


CHART 3—FUNCTION $F_0$

$$\sum_{1}^{n} - C_n F_o\,(u_n x, K_n) = \Delta W_c \frac{p}{2\pi} \log R/x$$

$$+ \Delta W_i \frac{p\,(\log R/x)\,(\log Rx/r^2)}{4\pi \log R/r}$$

$$+ (\Delta W_c + \Delta W_i + \Delta W_s)\,E \qquad (\mathbf{12})$$

by evaluating both sides for $n$ different values of $x$, and solving the resulting simultaneous equations in $C_n$. All quantities, such as $p$, $q$, $R$, $W_c$, $c$, etc., in the expressions for temperature and oil flow transients are readily obtained from Table I, or by well-known methods which require no explanation.

It is best to obtain one set of values of $C_n$ corresponding to unit change in copper loss, another set corresponding to unit change in dielectric loss, and a third set corresponding to unit change in sheath loss. These are used to calculate the temperature or oil flow transients separately for unit changes in each of copper, dielectric, or sheath losses. The transients need be calculated only once for a given cable, since, by the superposition principle, for any particular problem these "unit transients" can be proportioned and added together in any ratio and combination desired, which is the work of but a few minutes.

The oil flows obtained from equations (**18**), (**19**), and (**20**) will be slightly in error for the first few moments of the transient, because only a few terms in the infinite series are used in obtaining numerical values, and the neglected terms are appreciable when $t$ is very small. The following correct expressions should be used for the initial instant ($t = 0$):

$$a_1 = -\ \Delta W_c Cc/Q_1$$
$$a_2 = -\ \Delta W_s Vv/Q_2$$
$$a_3 = -\ \Delta W_i \epsilon/q$$

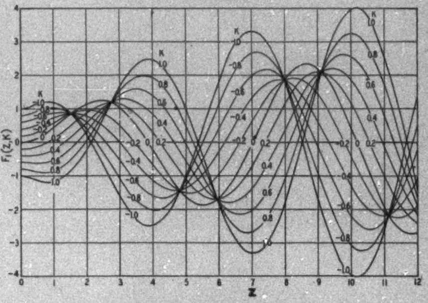


CHART 4—FUNCTION $F_1$

It is apparent that a small discrepancy between measured and calculated values for the initial part of the oil demand curves is not conclusive evidence of void formation in oil-filled cable, as some have maintained.[2,3,4]

## SOLUTION FOR GENERAL LOADING

The transient part of the expressions for temperature variations and oil flows due to rectangular load changes

TABLE I—PROPERTIES OF CABLE MATERIALS

| Material | Specific gravity | Weight lb./cu. in. | Thermal capacity Joules/cu. cm./°C. | Thermal capacity Joules/cu. in./°C. | Thermal capacity Joules/lb./°C | Thermal resistivity °C./watt/cu. cm. |
|---|---|---|---|---|---|---|
| Water | 1.00 | 0.0361 | 4.18 | 68.6 | 1900 | 171 |
| Copper | 8.95 | 0.3230 | 3.44 | 56.4 | 175 | 0.285 |
| Lead | 11.37 | 0.4110 | 1.43 | 23.4 | 57 | 2.990 |
| Transf. oil | 0.90 | 0.0325 | 1.90 | 31.1 | 957 | 611 |
| Dry paper | 1.41 | 0.0508 | 2.26 | 37.1 | 730 | 770 |
| Oil-filled insulation | 1.15 | 0.0415 | 2.10 | 34.5 | 832 | 550 |

The weight of copper conductor is 3.15 lb. and its thermal capacity 551 joules per deg. cent. per circular-inch foot, as ordinarily stranded and cabled.

The weight of lead sheath is 15.5 Dd lb. and its thermal capacity is 883 Dd Joules per deg. cent. per foot, where D and d are the average diameter and thickness in inches.

has been shown to be a rapidly converging, infinite series, each term of which reduces to a constant numerical coefficient multiplied by the simple exponential $e^{-\lambda t}$. For example, the numerical coefficients for use in temperature equations are $C_nF_o(u_nx, K_n)$, where $C_n$ is for unit change in loss. The "unit" results are fitted to a particular problem by multiplying by $\Delta W$, the actual number of units of loss change involved.

The unit coefficients were employed because they can be used directly in the Duhamel integral, a well-known application of the superposition principle by means of which the "rectangular" solution may be readily generalized. For the entirely general load curve of Fig. 12, the general solution for temperature at any point $x$ is:

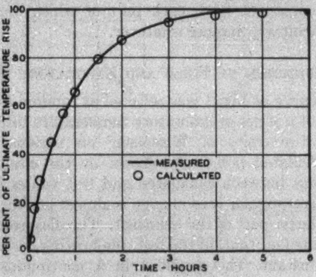


FIG. 1—COPPER TEMPERATURE TRANSIENT DUE TO ABRUPT CHANGE IN COPPER LOSSES

One-conductor 500,000-cir. mil cable having 26/64 in. ordinary insulation and 7/64 in. lead sheath

$$T = \sum^{n} C_nF_o(u_nx, K_n)L_n(W,t) + (W_c)_t \frac{p}{2\pi} \log R/x$$

$$+ (W_i)_t \frac{p}{4\pi \log R/r} (\log R/x) (\log Rx/r^2)$$

$$+ E\,(W_c + W_i + W_s)_t + T_o \qquad (31)$$

The last four terms in the above equation differ from the corresponding "steady state" terms in the rectangular solution only in that instead of using the constant watts loss after the transient, indicated by superscript ("), the varying watts loss during the transient, indicated by subscript "$t$," is used, as explained below. The summation term is identical with the corresponding term in the rectangular solution, except that $L_n(W, t)$ is substituted for $e^{-\lambda_n t}$. The load function $L(W, t)$ is known as the Duhamel integral, and for the present purpose is as follows:

$$L_n\,(W, t) = \left[\ \lambda_n e^{-\lambda_n t} \int_0^t (W_t - W_o) e^{\lambda_n t}\,dt - (W_t - W_o)\ \right] \qquad (27)$$

The $L$ function consists of two parts, one the instantaneous value of the load $(W_t - W_o)$ at the instant $t$ under consideration, and the other an integral from zero time up to the same instant $t$. Physically one part represents the effect of the load at the time considered, the other part represents the effect of all previous load. From this it follows that the upper limit $t$ on the integral and $t$ in all terms external to the integral are identical.

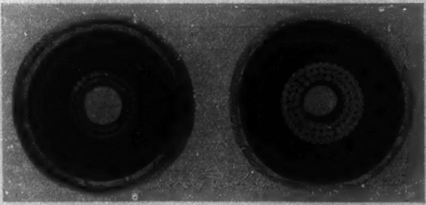
When the losses $(W)_t$ can be expressed as a mathematical function of $t$, the integral can be formally evaluated. For practical load curves this is seldom the case, and a graphical or a step-by-step method must be employed. For the step-by-step or tabular method the load function is rewritten in approximate form:

$$L(W,t) = \left[\ \lambda_n \Delta t\, e^{-\lambda_n t} \sum_{t=0}^{t=t} (W_t - W_o)/e^{-\lambda_n t} - (W_t - W_o)\ \right]$$

The expression under the summation sign is to be evaluated point by point up to time $t$ (or to point $B$, Fig. 12), using equal finite intervals of time $\Delta t$ for the preceding period. For good accuracy $\lambda_n \Delta t$ should not exceed 0.5 and it is best to use the average values of $W_t$ and $t$ for each increment term under the summation sign. $\lambda_n$ is exactly the same as for the rectangular solution. A complete numerical example of the evaluation of a load function is given in Appendix IV, Table IV.

At the instant of an abrupt discontinuity in $(W)_t$, the values of $L(W, t)$ for use in temperature equations are:

$$\Delta L_{cn} = -\ \Delta W_c$$
$$\Delta L_{in} = -\ \Delta W_i$$
$$\Delta L_{sn} = -\ \Delta W_s$$



Cable for line 7401 Cable for line 7406

FIG. 2—OIL-FILLED CABLES USED FOR NORTHWEST-DEVON 132-KV. LINES IN CHICAGO

and for oil flow equations, the correct values of oil flow are calculated directly from:

$$\Delta a_1 = -\ \Delta W_c Cc/Q_1$$
$$\Delta a_2 = -\ \Delta W_s Vv/Q_2$$
$$\Delta a_3 = -\ \Delta W_i \epsilon/q$$

for the same reasons discussed in connection with the solution for rectangular load change.

One load function $L_n(W, t)$ is required for every coefficient $C_n$ employed in the rectangular solution. For the complete solution, nine load functions are required, one for each of the three series terms used for each of the three losses, copper, dielectric, and sheath. Of course, when sheath and conductor losses are proportional, the resulting load functions are proportional. Any temperature or oil demand transient corresponding to any general load variation may be found by multiplying the load functions by the appropriate unit coefficients (determined from the rectangular solution), and summing. All the complete equations for general temperatures and oil flows are given in Appendix II.

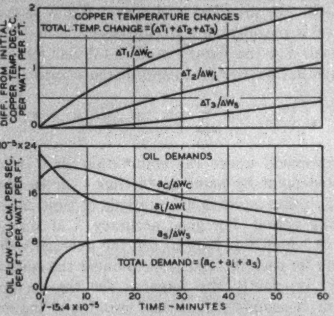


FIG. 3—TEMPERATURE AND OIL FLOW TRANSIENTS FOR CABLE OF LINE 7401, DUE TO UNIT CHANGES IN LOSSES

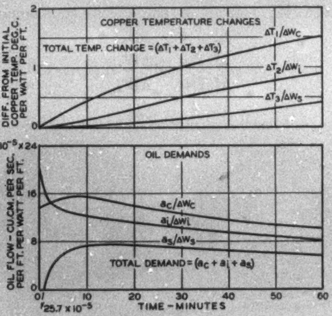


FIG. 4—TEMPERATURE AND OIL FLOW TRANSIENTS FOR CABLE OF LINE 7406, DUE TO UNIT CHANGES IN LOSSES

It is interesting to observe that the final solution for general load variation is based on assuming that a steady load $W_o$ precedes the load variations in which one is interested. (See Fig. 12.) This would seldom be the case, but a start must be made somewhere, and a good approximation is obtained by taking $W_o$ equal to the average load over the period preceding the interval to be investigated. Incidentally, it may be remarked that, if sufficient time is allowed to elapse, the effects of past load changes always shrink into insignificance. Hence, any initial conditions whatever may be selected, provided the start is made sufficiently long before the time at which correct results are desired.

Typical load functions and corresponding temperatures for various time exponentials are shown in Fig. 6. It will be noted that the load function displays all the required characteristics. This seems to be an ideally simple solution for such a complicated problem involving the general space-time thermal transient for a three-component load, each part of which may vary in any arbitrary manner whatever.

## VERIFICATION BY FIELD AND LABORATORY TESTS

The curve of Fig. 1 was selected at random from the results of a series of laboratory temperature tests made at the University of Wisconsin[7] on various cables. The calculated points are shown by the circles. The agreement between calculated and test values for this case of rectangular load change is almost perfect except for the latter part of the transient. The disagreement is due to the fact that, in the test, the heating current was kept constant. This resulted in a continuous slight increase in the conductor losses, due to increases in copper resistance resulting from the rising conductor temperature. The calculations, however, are based on the assumption that the conductor loss remains constant after the transient is initiated. The last few calculated points, therefore, fall slightly below the test points.

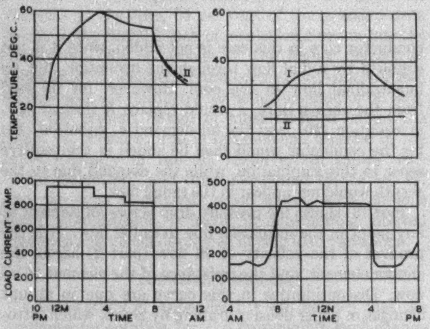
Heat runs which were conducted in Chicago on the two Northwest-Devon 132-kv. oil-filled lines Nos. 7401 and 7406 have provided further verification of the theoretical work. Complete agreement between calculated and test results could not be expected for two main reasons:

1. Duct conditions varied considerably from manhole to manhole along the line.
2. The measured rates of oil flow were determined from oil volume-time measurements on each phase. The changing oil volumes could not be measured precisely due to the nature of the oil reservoirs.

In the check calculations, some of the work concerned longitudinal pressure drops in cable cores and oil feed pipes under various conditions, and pressure-volume characteristics of oil reservoirs. Much of the underlying theory has been developed and published by others,[1,3,4] and is not given here.

The cables of the two lines which were tested are shown in Fig. 2. Line 7401 is made up of 600,000-cir. mil, single-conductor, oil-filled cable having 0.72-inch insulation, 0.69-inch hollow core, and a double reinforced sheath. Sheath losses are present, the ratio of sheath to copper losses being about 1:1. The line is divided into six one-mile sections, fed by gravity reservoirs at one end. A fairly thick oil (G. E. 118) is used. Line 7406 is made up of 1,100,000-cir. mil cable with a single lead alloy sheath. Sheath losses are eliminated. The oil used (G. E. 5314) is thinner than for line 7401. In addition to six one-mile gravity-fed sections, there is one-half mile balanced pressure section. Most of the gravity-fed sections of both lines have booster pressure reservoirs at the far end, which were disconnected during the tests.

The calculated unit temperature and oil flow transients for the two lines are shown in Figs. 3 and 4. The load variations used during the tests are shown in Fig. 5, with the corresponding calculated copper temperatures. During one part of the test on line 7406, the copper temperature was carefully measured by the copper-resistance method. The measured and calculated values agree almost exactly for the first two hours.



Line 7406—First test
I—Calculated copper temperature
II—Measured copper temperature

Line 7401
I—Calculated copper temperature
II—Measured duct temperature

FIG. 5—TEST CURRENTS AND CABLE TEMPERATURES DURING HEAT RUNS ON NORTHWEST-DEVON 132-KV. CABLES

At the end of the third hour, the calculated temperature shows a tendency to decrease more rapidly than it should. This probably indicates that some of the assumed constants of the cable are not perfectly correct. More accurate experimental values are needed for the temperature coefficient of expansion of oil-filled insulation, specific heat capacity of insulation, and other similar constants. It may not be out of place to point out here that most of the so-called thermal constants are only relatively constant. Usually they will be found to vary appreciably with temperature.

A comparison of the theoretical maximum rates of oil flow and the corresponding measured values are given in Table II. The agreement is fairly good, and it is probable that most of the error is in the measured values, due to the difficulty in getting accurate oil volume measurements.

From the calculated oil demands, and the oil viscosities corresponding to the calculated copper temperatures, the maximum and minimum pressures occurring in the cable core were calculated. Only sections on which the boosters were disconnected were considered, since the theoretical complications introduced by the presence of boosters would render such sections unsatisfactory for check purposes. The calculated and measured pressures are given in Table III, and the agreement is seen to be remarkably good.

The theory has provided a complete reconstruction of transient conditions on these two widely different oil-filled cables. The agreement with measured values is excellent, even under the difficult conditions associated with field tests on actual lines.

## PRESSURE DISTRIBUTION IN INSULATION

The principal object or purpose of oil-filled cable is the prevention of free gas spaces or open voids in the insulation. One of the chief causes of formation of such voids is the thermal shrinkage of the oil during decreases in cable loading. With the complete solution of the thermal transient available, a thorough investigation can be made of the possibility of this happening from an oil pressure standpoint for any assumed load conditions.

The pressure drop across the wall of insulation depends on the resistance of the paper tapes to radial oil flow. The insulation of commercial cables is often arranged in zones, the density of the paper tapes being different for each zone. It is necessary to know the dimensions of these zones, and their respective coefficients of friction to radial oil flow. Actual values for the latter have been found to range from 50 to 500 near the sheath, and 400 to 1,000 near the conductor, the

TABLE II—COMPARISON OF MEASURED AND CALCULATED MAXIMUM RATES OF OIL FLOW DURING HEAT RUNS ON NORTH-WEST-DEVON, 132-KV. CABLES

| Line 7401 | | | | Line 7406 | | | |
|---|---|---|---|---|---|---|---|
| Load-amps. | | Max. rate of flow gal. per hr. | | Load-amps. | | Max. rate of flow gal. per hr. | |
| Initial | Final | Measured* | Calc. | Initial | Final | Measured† | Calc. |
| | | | | First test: | | | |
| 160 | 420 | $6.6 \times 10^{-4}$ | $7.2 \times 10^{-4}$ | 0 | 950 | $12.7 \times 10^{-4}$ | $13.1 \times 10^{-4}$ |
| 400 | 150 | $7.3 \times 10^{-4}$ | $7.0 \times 10^{-4}$ | 830 | 0 | $11.3 \times 10^{-4}$ | $11.2 \times 10^{-4}$ |
| | | | | Second test: | | | |
| | | | | 0 | 800 | $7.1 \times 10^{-4}$ | $9.3 \times 10^{-4}$ |
| | | | | 800 | 0 | $8.2 \times 10^{-4}$ | $10.4 \times 10^{-4}$ |

*Average value for 6 sections.
†Average value for 3 to 6 sections.

TABLE III—COMPARISON OF MEASURED AND CALCULATED OIL PRESSURES IN CABLE CORES DURING HEAT RUNS ON NORTHWEST-DEVON, 132-KV. CABLES

| | Line 7401<br>Oil pressure-lb. per sq. in. | | | | Line 7406 (second test)<br>Oil pressure-lb. per sq. in. | | | |
|---|---|---|---|---|---|---|---|---|
| | Maximum | | Minimum | | Maximum | | Minimum | |
| Sec. No. | Meas. | Calc. | Meas. | Calc. | Meas. | Calc. | Meas. | Calc. |
| 1 | 28.5 | 29.4 | 15.5 | 14.4 | | | | |
| 2 | 26.0 | 26.0 | 12.0 | 11.4 | | | | |
| 3 | 25.0 | 24.4 | 13.0 | 12.6 | 20.5 | 19.2 | 8.0 | 7.3 |
| 4 | 26.0 | 24.1 | 15.0 | 14.0 | 20.0 | 19.5 | 8.0 | 6.2 |
| 5 | 26.0* | 25.0 | 13.0 | 12.5 | | | | |
| 6 | 38.0* | 37.9 | 16.0 | 16.8 | 10.0† | 8.6 | 2.0 | 2.1 |

*Estimated. Boosters were reconnected at peak pressure.

†Balanced pressure section. Reservoirs disconnected at one end.

units being (lb. per sq. in.) per (inch cube) per (cu. in. of oil per hr.) for oil having a viscosity of 50 centipoises.

The process of solution for the radial pressure drop due to a rectangular load change is illustrated diagrammatically in Fig. 7. For general load variation the generalized form of the rectangular solution should be used. Some graphical integrations will be required in either case, and in making these it is best to divide the radius in equal elements $\Delta x$, and to use the average values of $x$ and functions of $x$ for each element in forming products, etc.

In part (1) of Fig. 7, the temperature distribution in the cable is shown for the selected instant of time. It is required for finding the oil viscosity, and is obtained from equation (**10**) or (**31**), using Chart 3.

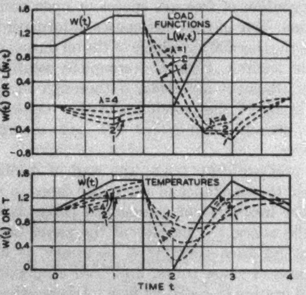


FIG. 6—GENERAL LOAD FUNCTIONS AND CORRESPONDING TEMPERATURES FOR TYPICAL LOAD CURVE

Part (2) shows the velocity of oil flow across the cylindrical surface at any point in the insulation, and for hollow core oil feed is obtained from equation (**20**) by replacing $r$ by $x$, and using Chart 4. For oil feed from a hollow core only, the contraction of the lead sheath will tend to supply the demand of some of the outer layers of insulation, and this should be taken into account. The oil supply due to the sheath is obtained from equation (**19**), using Chart 3. This is added, in the negative sense, to the integrated demand of the insulation. The demand due to the contraction of the conductor core in this case is not added, since it is not supplied by radial flow through the insulation, but by longitudinal flow in the core. However, for oil feed from the sheath only, $x$ would replace $R$ instead of $r$, in equation (**20**), and the oil demand $a_1$ equation (**18**) for the conductor would then be added in the positive sense to this summation, while the demand due to the sheath would not appear in the radial flow.

Part (3) shows the pressure drop across an element at any point in the insulation due to radial flow. It is the product of the velocity of oil flow (part 2) across the chosen element, and the resistance of the element to oil flow. Discontinuities in this curve are due to abrupt changes in paper density grading by zones, which introduce discontinuities in the insulation oil flow resistance factor, $\rho$. The viscosity factor, $\mu$, takes care of the variation of viscosity from element to element, due to the temperature distribution shown in part (1). The pressure drop is zero where the velocity is zero; in other words, where the supply due to the sheath has been exactly consumed by the demand due to the outer layers of insulation.

The total pressure drop due to radial flow is shown in part (4). It is the summation of the pressure drops across all the elements. This falls into two parts, since at some point in the insulation the pressure drop is zero. The pressure required at the core to supply the radial flow is the summation taken from the point of zero drop inwards to the conductor. The summation taken outwards from the zero point to the sheath is the pressure existing under the sheath due to its contraction. These pressures, part (4), must of course be altered by an additive constant for hydrostatic pressure so as to make the pressure at the inside (or outside) radius of the insulation equal to the pressure in the oil core (or sheath channels) at the moment under consideration. If the final resultant pressure is anywhere less than the partial pressure of solution of gases absorbed in the oil, then presumably voids will form. Influence of capillary attraction and electric stress on void formation, although important, are outside the scope of this paper.

When the insulation has oil feed from both core and sheath, then radial pressure drops are computed for expansion or shrinkage of the insulation only. Zero oil flow points in the insulation are assumed, by cut and try, to yield radial drops with a pressure difference equal to the difference of pressures actually existing between the two oil-feed sources.

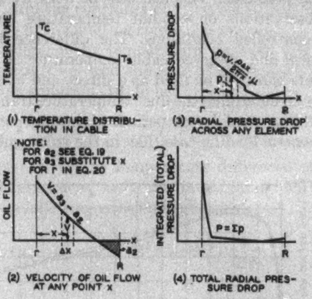
Following the procedure outlined, a graphical solution of the radial pressure drop was computed for the cable of line 7401. Under the most severe conditions of dropping load in the winter, the radial pressure drop was only a fraction of a pound per square inch, or much less than the minimum permissible oil pressure in the core. The radial distribution of the pressure drop is of interest. In spite of the higher temperature and smaller oil viscosity at the core, 50 per cent of the pressure drop occurs in the first 0.1 inch of insulation surrounding the conductor. This is because of the higher density of paper grading, smaller circumference, and concentrated oil flow near the conductor for hollow-conductor oil feed.

In the present design of most oil-filled cables the radial oil pressure drop is insignificant because of the small viscosity of the oil. However, in cables with "solid insulation" and thick compound this is not so, and the type of analysis given above, with obvious slight modifications, is useful in determining internal pressures and vacua developed during load variations.

## General Remarks

From a study of Appendix I it will be seen that the fundamental solution for the rectangular load change comes out in terms of Bessel functions (see equations (**5**), (**15**), (**16**), (**17**)). It will be seen also that it is necessary to evaluate the ratio of two constants (*A* and *B*) and roots *u* of a transcendental expression in Bessel functions, entailing a very great deal of complication and labor. In the simplified method given in the text, all necessity for any knowledge whatever of Bessel functions has been eliminated by Charts 1, 2, 3, and 4. Charts 1 and 2 also perform the operation of finding the roots of the transcendental expression. The saving in labor is so great that a novice using the simplified methods can work out the complete solution for temperatures and oil flows in a day, whereas without the aid of the charts it would require several days. In fact, the precise calculations of thermal and oil flow transients have been reduced to a form of such easy and prompt numerical application as to displace successfully less exact approximate methods on the criterion of ease and convenience alone.

The methods described in this paper were developed for problems of single-conductor cables. They can also be applied directly to three-conductor cables, using a per phase basis (*e. g.*, sheath thermal resistance = 3*E*, etc.). For oil-filled three-conductor shielded cable with round conductors, the accuracy will be excellent. If the conductors are sector-shaped, good accuracy may be obtained by using the equivalent round conductors. For ordinary three-conductor cable with solid fillers and no shielding, the accuracy will be only fair.



(1) TEMPERATURE DISTRIBUTION IN CABLE

(3) RADIAL PRESSURE DROP ACROSS ANY ELEMENT

(2) VELOCITY OF OIL FLOW AT ANY POINT x

(4) TOTAL RADIAL PRESSURE DROP

Fig. 7—Solution for Radial Oil Pressure Drop in Cable Insulation

Illustration is for cable having oil feed from hollow core only

The assumption (**6**) that the thermal properties of a cable are constants is only approximately true. These properties do vary with temperature, but only slightly. Test data are inadequate, however, and the mode of variation is unknown, so that the assumption is a mathematical necessity. Some slight errors in results may be expected from this source.

Assumption (**5**) concerning dielectric loss permits the heat flow equations to be written for the dielectric loss very nearly as it actually exists in the cable. Other

TABLE IV—TABULAR METHOD OF EVALUATING $L(W, t)$

Example for load curve of Fig. 6, when $\lambda = 1$. Let $\Delta t = 0.5$

| (1) time, $t$ | | (2) $(W_t - W_0)$ | | (3) $e^{-\lambda t}$ | | (4) $\frac{(W_t - W_0)}{e^{-\lambda t}}$ | (5) $\sum_0^t (4)$ | (6) | (7) |
|---|---|---|---|---|---|---|---|---|---|
| $E$* | $A$* | $E$ | $A$ | $E$ | $A$ | | | $(\lambda \Delta t e^{-\lambda t})(5)$ | $L(W, t) = (6) - (2)$ |
| 0.00 | | 0.000 | | 1.000 | | 0.000 | 0.000 | 0.000 | 0.000 |
| | 0.25 | | 0.125 | | 0.779 | 0.161 | | | |
| 0.50 | | 0.250 | | 0.607 | | | 0.161 | 0.049 | −0.201 |
| | 0.75 | | 0.375 | | 0.472 | 0.795 | | | |
| 1.00 | | 0.500 | | 0.368 | | | 0.956 | 0.176 | −0.324 |
| | 1.25 | | 0.500 | | 0.286 | 1.745 | | | |
| 1.50 | | 0.500 | | 0.223 | | | 2.701 | 0.302 | −0.198 |
| | 1.75 | | −1.000 | | 0.175 | −5.71 | | | |
| 2.00 | | −1.000 | | 0.135 | | | −3.01 | −0.203 | +0.797 |
| etc. | | | | | | | | | etc. |

*$E$ and $A$ refer to values at end of increments and average values during increments, respectively.

investigators[2,3] have been content to assume, for the sake of simplicity, that the dielectric loss is concentrated at the conductor or sheath, or divided between them. The error due to this assumption is illustrated in Fig. 8.

Field tests indicate that the convenient assumption of constant duct temperature holds for the first one or two hours of the transient, but for longer times or very large change in total heat losses the changes in duct temperature must be taken into account. The accuracy with which cable transients can now be handled justifies the removal of this remaining major source of error in practical problems. This can best be done by study of field observations on conduit temperature transients under controlled conditions. The difference between theoretical and observed cable temperature or oil flow transients can now be used as a direct and convenient measure to determine the duct temperature transient.

Since, in general, longer periods of time are considered in the general loading case than in the rectangular case, any inaccuracies in thermal constants or changes in duct temperature may accumulate to appreciable error, the duct temperature transient being by far the most important. In such cases some empirical correction for duct temperature should be made.

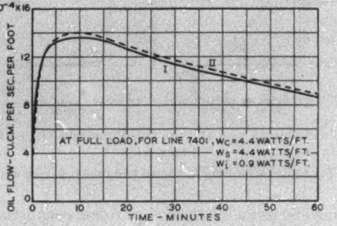


FIG. 8—OIL DEMAND OF TYPICAL CABLE (LINE 7401) DUE TO DROPPING FULL LOAD, AND VOLTAGE

I—Dielectric loss properly distributed in insulation
II—Dielectric loss assumed concentrated at conductor

## CONCLUSIONS

1. A reasonably simple solution has been obtained for cable transients due to a rectangular load change. The dielectric loss is distributed properly throughout the insulation. The theory has been verified by measurements on actual cables of the ordinary and oil-filled type.

2. Mathematical and graphical aids have been developed, which greatly reduce the time and labor required for numerical work. Solution and verification of a complete problem formerly required about a week. The same results can now be obtained in one day, with the aid of the new methods.

3. The transients due to load variations of any complexity whatever have been solved by using the well-known superposition theorem. The numerical work is very simple, and any desired degree of accuracy can be obtained.

4. A solution for the pressure distribution in the body of the insulation has been developed.

5. Some of the constants of cable insulation needed for use in thermal and oil-flow problems are relatively new. Many of the values now in use for these constants are based on only a few scattered observations. Further laboratory and field data should be obtained.

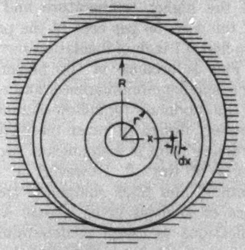


FIG. 9—CABLE IN DUCT

## ACKNOWLEDGMENT

The authors wish to acknowledge valuable suggestions regarding this paper, from Mr. Elwood Church of the Edison Electric Illuminating Company of Boston. They also desire to express appreciation to the Commonwealth Edison Company and to the Utilities Research Commission for assistance in its preparation.

## Appendix I

### SOLUTION FOR INSTANTANEOUS LOAD CHANGE

*Temperatures*

For any single-conductor cable such as shown in Fig. 9, the fundamental temperature equations in space and time for a change in losses of the type shown in Fig. 10 are:

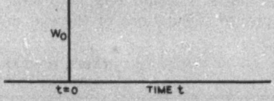


FIG. 10—RECTANGULAR LOAD CHANGE

$$-W = \frac{2\pi x}{p}\,\frac{\partial T}{\partial x} \tag{1}$$

$$\frac{\partial T}{\partial t} = \frac{2\pi x\,dx\left(\dfrac{KV}{x\log R/r}\right)^2 w - \dfrac{\partial W}{\partial x}\,dx}{2\pi x\,dx\,q} \tag{2}$$

Assuming the power factor of the dielectric is uniform,

$$W_i = \frac{2\pi(KV)^2 w}{\log R/r} \tag{3}$$

From equations (**1**), (**2**), and (**3**) we get:

$$pq\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{1}{x}\frac{\partial T}{\partial x} + \frac{pW_i}{2\pi x^2 \log R/r} \tag{4}$$

The complete solution of equation (**4**) is:

$$\begin{aligned} T = &\sum_{n=1}^{n=\infty} e^{-\frac{u_n^2}{pq}t}\,[A_n J_o(u_n x) + B_n Y_o(u_n x)] \\ &+ \frac{W_c''}{2\pi}\,p \log\frac{R}{x} \\ &+ \frac{p(W_i'')}{4\pi\log R/r}\left(\log\frac{R}{x}\right)\left(\log\frac{Rx}{r^2}\right) \\ &+ (W_c'' + W_i'' + W_s'')\,E + T_o \end{aligned} \tag{5}$$

where $J_o$ and $Y_o$ are Bessel functions of the first and second kinds respectively, both of order zero.

Applying the boundary conditions for $x = r$ and $x = R$, it can be shown[1] that:

$$\begin{aligned} B_n/A_n &= -\left[\frac{M_1 - \phi(z\,.\,r/R)}{M_1 - \psi(z\,.\,r/R)}\right]\theta(z\,.\,r/R) \\ &= -\left[\frac{(N/z^2 - M_2) - \phi(z)}{(N/z^2 - M_2) - \psi(z)}\right]\theta(z) \\ &= P(M_1, r/R, z) = Q(N, M_2, z) \end{aligned} \tag{6}$$

where

$$M_1 = \frac{Q_1}{2\pi q r^2},\ M_2 = \frac{Q_2}{2\pi q R^2},\ N = \frac{p}{2\pi E},\ z = Ru$$

and

$$\phi(y) = \frac{J_1(y)}{yJ_o(y)},\ \psi(y) = \frac{Y_1(y)}{yY_o(y)},\ \theta(y) = \frac{J_o(y)}{Y_o(y)} \tag{7}$$

The roots $u$ and the coefficient ratios $B/A$ for use in equation (**5**) are obtained from equation (**6**), preferably by graphical solution. The first three are generally sufficient. $A$ and $B$ are seen to be interdependent, and the ratio $B/A$ (the $P$ and $Q$ functions of equation (**6**)) will be found to vary from minus infinity to plus infinity. This is highly inconvenient in graphical work, and can be avoided by introducing the transformation:

$$K = (B/A)/(1 + |B/A|)$$

since the values of $K$ vary only from minus one to plus one.

It is useful to combine the $J$ and $Y$ Bessel functions, defining single new functions involving $K$ instead of $B/A$ as follows:

$$F_o(z, K) = (1 - |K|)\,J_o(z) + KY_o(z) \tag{8}$$

$$F_1(z, K) = (1 - |K|)\,zJ_1(z) + KzY_1(z) \tag{9}$$

and to introduce the abbreviation:

$$\lambda_n = u_n^2/pq$$

Equation (**5**) may now be rewritten:

$$\begin{aligned} T = &\sum^{n} e^{-\lambda_n t}\,C_n F_o(u_n x, K_n) + \frac{W_c'' p}{2\pi}\log\frac{R}{x} \\ &+ \frac{pW_i''}{4\pi\log R/r}\left(\log\frac{R}{x}\right)\left(\log\frac{Rx}{r^2}\right) \\ &+ (W_c'' + W_i'' + W_s'')\,E + T_o \end{aligned} \tag{10}$$

where $C_n$ are the constants of integration, and must be selected to fit the limiting conditions in time.

The difference in temperature between the initial steady state ($t=o$) and the final steady state ($t=\infty$) is found from equation (**10**) to be:

$$T' - T'' = \sum^{n} C_n F_o(u_n x, K_n) \tag{11}$$

Equating (**11**) to the temperature difference obtained by consideration of only the initial and final steady states, the following relation is obtained:

$$\begin{aligned} \sum^{n} C_n F_o(u_n x, K_n) = &\left[(W_c' - W_c'')\frac{p}{2\pi}\log\frac{R}{x}\right] \\ &+ \left[(W_i' - W_i'')\frac{p(\log R/x)(\log Rx/r^2)}{4\pi\log R/r}\right] \\ &+ [(W_c' - W_c'') + (W_i' - W_i'') + (W_s' - W_s'')]E \end{aligned} \tag{12}$$

The numerical values of $C_n$ are obtained from equation (**12**). This is preferably done by evaluating all terms for as many different values of $x$ as there are roots required, and solving the resulting simultaneous equations in $C_n$. The first three values of $n$ are usually sufficient.

Equation (**10**) is now completely determined, and the temperature transients of the conductor and sheath may be obtained at once by making $x = r$ and $x = R$ in equation (**10**).

### *Oil Demands*

The three components of the total oil flow, due to variation in volume of the conductor, the sheath, and the insulation are readily seen to be:

$$a_1 = -\,Cc\,\frac{\partial T_c}{\partial t} \tag{15}$$

$$a_2 = -\,Vv\,\frac{\partial T_s}{\partial t} \tag{16}$$

$$a_3 = -\int_r^R \epsilon\,(2\pi x\,dx)\,\frac{\partial T}{\partial t} \tag{17}$$

The negative sign is introduced to make the flow positive (by definition) when the cable is cooling.

Performing the indicated operations on $T_c$, $T_s$, and $T$, the following expressions result, for unit change in loss:

$$a_1 = \frac{Cc}{pq} \Sigma u_n^2 e^{-\lambda_n t} C_n F_o(u_n r, K_n) = \Sigma f_{1n} e^{-\lambda_n t} \tag{18}$$

$$a_2 = \frac{Vv}{pq} \Sigma u_n^2 e^{-\lambda_n t} C_n F_o(u_n R, K_n) = \Sigma f_{2n} e^{-\lambda_n t} \tag{19}$$

$$a_3 = \frac{2\pi\epsilon}{pq} \Sigma e^{-\lambda_n t} C_n [F_1(u_n R, K_n) - F_1(u_n r, K_n)]$$
$$= \Sigma f_{3n} e^{-\lambda_n t} \tag{20}$$

For a unit change in copper loss only, the total oil demand would be $a_c = (a_1 - a_2 + a_3) = \Sigma f_{cn} e^{-\lambda_n t}$, and the same is true for changes in dielectric loss or sheath loss.

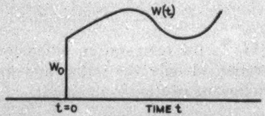


FIG. 11—FUNCTIONAL LOAD VARIATION

### *General Expressions for Oil Demands and Temperature Transients*

Indicating copper, dielectric and sheath losses by subscripts $c$, $i$, and $s$, respectively, and letting subscript $n$ with $\overset{n}{\Sigma}$ refer to the summation with respect to successive time constants $\lambda_n$, the total oil demand due to an instantaneous change $\Delta W$ in any or all of the three losses can be written:

$$a = \overset{n}{\Sigma} [f_{cn} \Delta W_c e^{-\lambda_n t} + f_{in} \Delta W_i e^{-\lambda_n t} + f_{sn} \Delta W_s e^{-\lambda_n t}] \tag{21}$$

In a similar manner the conductor and sheath temperatures can be written:

$$T_c = \overset{n}{\Sigma} [g_{cn} \Delta W_c e^{-\lambda_n t} + g_{in} \Delta W_i e^{-\lambda_n t} + g_{sn} \Delta W_s e^{-\lambda_n t}]$$
$$+ G(W_c'' + W_i''/2) + E(W_c'' + W_i'' + W_s'') + T_o \tag{22}$$

$$T_s = \overset{n}{\Sigma} [h_{cn} \Delta W_c e^{-n\lambda t} + h_{in} \Delta W_i e^{-\lambda_n t} + h_{sn} \Delta W_s e^{-\lambda_n t}]$$
$$+ E(W_c'' + W_i'' + W_s'') + T_o \tag{23}$$

In equations (**21**), (**22**) and (**23**) the coefficients $f$, $g$, and $h$ and the exponents $\lambda_n$ have already been determined.

## Appendix II

### SOLUTION FOR GENERAL LOAD VARIATION

Assume, first, that instead of the load remaining constant after the initial instantaneous change as shown in Fig. 10, it varies with time in any manner whatever, as indicated by $W(t)$ in Fig. 11. Duhamel's integral is applicable to this case. From equation (**21**), the "unit function" for oil flow, expressed for only one typical element, is:

$$a = f \Delta W e^{-\lambda t} \tag{24}$$

where $f$ and $\Delta W$ are numerical constants.

Following Duhamel's integral, the general equation for oil flow due to load change of the type shown in Fig. 11 is readily found to be:

$$a = -f \left[ W(t) - \lambda e^{-\lambda t} \int_{v=0}^{v=t} e^{\lambda v} W(v)\, dv \right] \tag{25}$$

where $v$ is a temporary integration variable which disappears when integration is performed and limits substituted. Since in this case $v$ is the only variable under the integral, any other variable may be substituted for $v$, say $t$.

For practical purposes, however, a solution for the type of load curve shown in Fig. 12 is more convenient than equation (**25**). The solution can obviously be obtained by subtracting from equation (**25**) the effect of the initial instantaneous change $W_o$. The resulting expression is:

$$a = -f \left[ \{ W(t) - W_o \} - \lambda e^{-\lambda t} \int_{v=0}^{v=t} e^{\lambda v} \{ W(v) - W_o \}\, dv \right] \tag{26}$$

This entirely general solution is equally applicable to any element of oil flow or temperature change, provided the proper coefficients, $f$, $g$, or $h$ of equations (**21**), (**22**), and (**23**) are employed. For the sake of brevity, it is convenient to substitute $t$ for $v$ and to define the following "load function:"

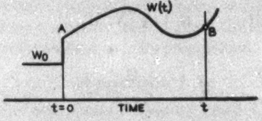


FIG. 12—GENERAL LOAD VARIATION

$$L_n = L_n(W, t) = \left[ \lambda_n e^{-\lambda_n t} \int_0^t \{ W(t) - W_o \} e^{+\lambda_n t}\, dt - \{ W(t) - W_o \} \right] \tag{27}$$

Summing up for the space harmonics $n$ and restoring subscripts for the three sources of losses, the completely general expressions for temperatures and oil flow may be written at once. They are:

$$a = \overset{n}{\Sigma} [f_{cn} L_{cn} + f_{in} L_{in} + f_{sn} L_{sn}] \tag{28}$$

$$T_c = \overset{n}{\Sigma} [g_{cn} L_{cn} + g_{in} L_{in} + g_{sn} L_{sn}] + G(W_c + W_i/2)_t$$
$$+ E(W_c + W_i + W_s)_t + T_o \tag{29}$$

$$T_s = \overset{n}{\Sigma} [h_{cn} L_{cn} + h_{in} L_{in} + h_{sn} L_{sn}] + E(W_c + W_i + W_s)_t + T_o \tag{30}$$

where subscript $t$ is substituted for functional notation $W(t)$.

The temperature at any point at any time for any general load variation is:

$$T_x = \sum^{n} [C_{cn}F_o(u_n x, K_n)L_{cn} + C_{in}F_o(u_n x, K_n)L_{in} + C_{sn}F_o(u_n x, K_n)L_{sn}] + (W_c)_t \frac{p}{2\pi} \log \frac{R}{x} + (W_i)_t \frac{p}{4\pi \log R/r} \left(\log \frac{R}{x}\right)\left(\log \frac{Rx}{r^2}\right) + E\,(W_c + W_i + W_s)_t + T_o \tag{31}$$

## Appendix III

### Theory of Charts 1 and 2

The roots of equation (**5**) are obtained from equation (**6**), which for convenience was abbreviated to the form:

$$B/A = P(M_1, r/R, z) = Q\,(N, M_2, z)$$

The direct method of solution by plotting the $P$ and $Q$ functions and reading off intersections is most feasible, but considerable labor is involved. $P$ and $Q$ pass repeatedly from minus to plus infinity, which is very awkward in the graphical solution for intersections. However, very satisfactory results are obtained by plotting $y = \tan^{-1}(30/19)(P)$ and $y = \tan^{-1}(30/19)(Q)$ against $z$, which, from the nature of Bessel functions and the form of $P$ and $Q$, reduces the curves to a series of nearly straight slanting lines between ± 90° instead of $\pm\infty$. But for $y$ there is one and only one corresponding value of $B/A$, and the same is true of $K$. Therefore, the $y$ axis can be labeled in terms of $K$ instead of degrees, which gives directly the values required for obtaining the $F_o$ and $F_1$ functions.

The quantity $r/R$ appears in $P$ only as a multiplier of $z$. By plotting $P$ and $Q$ directly against log $z$ as abscissas, any value of $r/R$ can be inserted in $P$ at will by a horizontal displacement of $P$ with respect to $Q$, of value $\log r/R$.

The $P$ and $Q$ functions have been calculated for a range of values of $M_1$, $M_2$, and $N$ sufficiently large to cover any reasonable design of cable. Instructions for use appear with the charts. The charts must be to the same scale.

## Appendix IV

### Routine Steps in Solutions for Transients

The most important operations in solving problems of cable transients are listed in sequence to serve as a guide in making actual computations. A few of the corresponding numerical values are given for line 7406. The figures should be of about the same order for any other cable, provided the design is not radically different. Some useful constants are given in Table I.

*1. Rectangular Load Change*

| Routine steps | | Numerical values for line 7406 | | | |
|---|---|---|---|---|---|
| 1—Calculate $M_1$, $M_2$, $N$, and $R/r$ | | $M_1 = 0.645$, $M_2 = 0.078$<br>$N = 1.910$, $R/r = 2.007$ | | | |
| 2—Find three roots from charts 1 and 2, obtaining $K_n$ and $Z_n$ | | $n = 1$ | $n = 2$ | $n = 3$ | |
| | $K_n =$ | $-0.0476$ | $0.2727$ | $-0.3254$ | |
| | $Z = ru_n =$ | $0.738$ | $2.214$ | $4.493$ | |
| 3—Find $F_o$ and $F_1$ functions from charts 3 and 4 | $F_o(ru_n, K_n) =$ | $0.833$ | $0.299$ | $-0.108$ | |
| | $F_1(ru_n, K_n) =$ | $0.312$ | $0.952$ | $-0.135$ | |
| 4—Calculate temperature at copper, mean insulation radius, and sheath for 1 watt loss | | For 1 watt/cm. copper loss<br>$(T_c - T_o) = 106.8$; $(T_m - T_o) = 71.0$<br>$(T_s - T_o) = 45.8$ | | | |
| 5—Set up and solve three simultaneous equations for $C_n$ | | (1) $0.833C_1 + 0.299C_2 - 0.108C_3 = 106.8$<br>(2) $0.670C_1 - 0.159C_2 + 0.220C_3 = 71.0$<br>(3) $0.467C_1 - 0.327C_2 - 0.185C_3 = 45.8$<br>$C_1 = 116.2$; $C_2 = 30.66$; $C_3 = -7.94$ | | | |
| 6—Multiply out the coefficients in the final equations | | In Eq. (**10**) for $T_c$ (copper loss only): | | | |
| | | $n = 1$ | $n = 2$ | $n = 3$ | Check |
| | $C_nF_o(u_nr, K_n)$ | 96.89 | 9.17 | 0.86 | 106.9 |
| | $u_n^2/pq$ | $1.34 \times 10^{-4}$ | $12.08 \times 10^{-4}$ | $49.60 \times 10^{-4}$ | |
| 7—Set up final equations, and solve for various values of $t$ | | Copper temperature transient due to change of 1 watt copper loss per cm ($t$ in minutes)<br>$T_c = 96.89e^{-0.00804t} + 9.17e^{-0.0725t} + 0.86e^{-0.298t}$ | | | |

*2. General Loading*

1—Obtain unit coefficients, using rectangular solution; for example, for line 7406 it was found that $g_{c1} = 96.89$, and $\lambda_1 = 0.00804$.

2—Arrange load curve in terms of copper, dielectric, and sheath loss.

3—Proceed according to Table IV, which is for $\lambda = 1$, and the hypothetical load curve of Fig. 6.

4—Multiply $L(W, t)$ by coefficients $f_n$ to obtain oil flow, and coefficients $g_n$ or $h_n$ for temperatures at copper and sheath.

## List of Symbols

$t$ = time in seconds
$r$ = inside radius of insulation
$R$ = outside radius of insulation
$x$ = radius of cylindrical element considered
$Q_1$ = total thermal capacity of copper conductor and free oil in strands and core (if any) per unit length, Joules per deg. cent.
$Q_2$ = total thermal capacity of sheath, armor, shielding tapes and free oil in channel or sheath flutes (if any) per unit length
$q$ = specific thermal capacity of insulation, per unit volume
$p$ = specific thermal resistance of insulation, per unit volume
$w$ = dielectric loss per unit volume at unit voltage gradient
$E$ = thermal resistance, sheath to duct, per unit length
$G$ = thermal resistance, copper to sheath, per unit length
$T$ = temperature deg. cent. at point and time considered
$T_o$ = duct temperature
$W$ = watts heat flow across cylindrical element at $x$
$W_c$ = watts copper loss
$W_i$ = watts dielectric loss per unit length of cable
$W_s$ = watts sheath loss
$C$ = total volume copper conductor and free oil per unit length
$V$ = total volume inside of lead sheath or inside of shielding tape, if any

$c$ = effective volumetric thermal coefficient of expansion of copper core and free oil combined, per deg. cent.

$\epsilon$ = effective volumetric thermal coefficient of expansion of insulation, oil and paper combined, per deg. cent.

$v$ = effective volumetric thermal coefficient of expansion of lead sheath, corrected for free oil in channel or sheath flutes, if any

$a_1$ = rate of oil flow contributed by conductor and core, cu. cm. per sec. per unit length

$a_2$ = rate of oil flow contributed by lead sheath shrinkage or expansion, corrected for oil in flutes or channels, if any

$a_3$ = rate of oil flow contributed by insulation

$a$ = total resultant rate of oil flow, per unit length

$\rho$ = resistivity of insulation to radial flow of oil of standard viscosity

$\mu$ = correction applied to $\rho$ to take account of actual viscosity of oil

$\Delta$ = finite increment of quantity considered

NOTE: Thermal "constants" are assumed independent of temperature.

Subscripts $c$, $i$, and $s$ refer to conductor, insulation, and sheath, respectively.

Superscript ($'$) indicates conditions before transient.

Superscript ($''$) indicates conditions during and after transient.

All logarithms are to base $e$.

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## Discussion

**E. A. Church:** A significant fact to be noted in this paper is the reduction of relatively difficult mathematics to simple arithmetic by the expedient of combining Bessel functions in charts enabling the coefficients and exponents in the temperature and oil demand equations to be evaluated in a minimum of time.

The method used by the authors enables discontinuities in the load curve to be taken into account with greater accuracy than some methods previously employed for computing temperatures under variable loading, a factor of extreme importance in computing stresses in oil filled cables, since the stress or void formations depend as much upon the rate of change of temperature as upon the temperature change itself. Sudden discontinuities on the load curve will create the greatest rates of change of temperature.

Another important fact which it is well to emphasize is that the temperature and oil demand equations for suddenly applied load (unit function in Heaviside terminology) *are functions of the constants of the cable only.* Thus only one computation of coefficients need ever be made for any given size and type of cable. These may be used for the solution of any load variation whatsoever, by an application of the Duhamel integral.

The Duhamel integral is applicable to any physical problem where the principal of superposition is valid. In the general case it is expressed as follows in a solution for temperature:

$$T(t) = Q(t)\,A(o) + \int_0^t \frac{\partial}{\partial t} A(t-\lambda)\,Q(\lambda)\,d\lambda.$$

where the terminology of the paper is used. $A(t)$ is the solution for the unit function and $A(o)$ its value at the initial instant: $\lambda$ is a variable time parameter under the integral sign which makes it difficult to evaluate in the general case. Where $A(t)$ can be expressed in the form of a series of exponential terms the integral takes the form shown in the paper and can be solved as an ordinary definite integral.

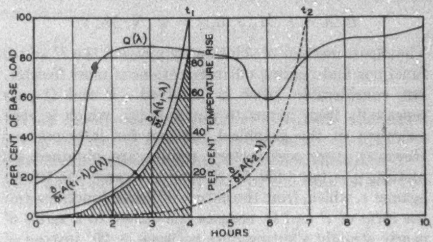

FIG. 1—ILLUSTRATION SHOWING METHOD OF INTEGRATING

$$\int_0^t \frac{\partial}{\partial t} A\,(t-\lambda)\,Q\,(\lambda)\,d\lambda$$

The shaded area represents:

$$\int_0^{t_1} \frac{\partial}{\partial t} A\,(t_1-\lambda)\,Q\,(\lambda)\,d\lambda$$

Hence, if the solution for a suddenly applied load can be obtained by test, the solution for any general load variation may be easily calculated from it, provided the test curve can be represented by a simple mathematical formula such as a series of exponentials. Theoretically it is quite possible to represent a curve of the type obtained in this problem by such a series, but the practical difficulties encountered in solving for the coefficients and exponents of each term of the series, even though only a few terms are used, make it easier to evaluate the integral graphically. This may be done as follows:

Plot the value of $\dfrac{\partial}{\partial t} A(t)$ on transparent paper to the same scale as a plot of the loading curve. Superimpose this plot of $\dfrac{\partial}{\partial t} A(t)$ reversed on the time axis, and with its origin shifted to the right of the origin of the loading curve an amount representing time $t_1$, as shown in the accompanying illustration. It then corresponds, on the scale of the loading curve, to $\frac{\partial}{\partial t} A(t - \lambda)$. Plot the product of $\frac{\partial}{\partial t} A(t - \lambda)$ and $Q(\lambda)$ and integrate this product curve from $o$ to $t$. Repeat this process from time $t_2$, and so on for all the values of time at which it is desired to compute the temperature.

It must be remembered that for every new value of $t$ chosen a separate product curve will be necessary, and is obtained by shifting the axis of the graph of $\frac{\partial}{\partial t} A(t - \lambda)$ to the new value of $t$. The plot of these various definite integrals will be the evaluation of $\int_0^t \frac{\partial}{\partial t} A(t - \lambda)\, Q(\lambda)\, d\lambda$. It is then a simple matter to add the other term of the Duhamel integral to obtain the complete temperature variation with respect to time. This graphical scheme of integration can be carried out very easily by means of a planimeter for obtaining the area under the product curve.

If a planimeter is available it may profitably be used in evaluating the coefficient, $L_n(W,t)$ in equations (**27**) and (**31**) of the paper rather than the step-by-step method described.

**F. H. Buller:** Those who have occasion to make temperature transient or oil demand calculations on cables are very much indebted to Messrs. Miller and Wollaston for the simplifications which they have devised to render computations less laborious.

The large scale editions of charts 1 and 2 have been found very useful in obtaining approximate values of the roots of equation (**6**). While the charts give values which are close enough for all but the most accurate work for the first root of the equation, we have found it advisable to check the values obtained from the charts by substituting in equation (**6**) and plotting in the usual way where greater accuracy is required, especially in the case of the roots of the higher order than the first. However, in most cases it is found that the charts give values which are close enough for approximate work; and even when more exact results are necessary the charts are very useful in reducing the amount of labor involved in the solution of equation (**6**) to an absolute minimum. We believe that the limitations of the charts lie in the mechanics of reproduction rather than in the underlying theory. As the authors point out, it should be theoretically possible to construct charts which would give any desired degree of accuracy from the equations presented in the paper.

The value of charts 3 and 4 in simplifying numerical calculations is so obvious as to require no comment.

The application of the principle of superposition to thermal calculations is, of course, not new; and the Duhamel integral has long been a familiar function. However, Messrs. Miller and Wollaston have given a very thoroughgoing treatment showing exactly how these aids to analysis can be applied to this particular problem and we feel that this treatment will be of such assistance to those who have to deal with this subject as to constitute a distinct advance in the art of thermal transient calculations.

The method of evaluating the coefficient $C_n$ described by the authors, is simple in theory and usually useful in practise, particularly if only three terms of the infinite series for temperature and oil demand are required. As the number of terms increases, it is found that the amount of numerical work involved in this method increases much more rapidly; and the method soon becomes rather unmanageable because of this. Under such conditions it is better to use the mathematical solution presented in the A.I.E.E. TRANS., December, 1931, pages 1411 to 1420, and the *G. E. Review*, September, 1931, by Mr. G. B. Shanklin and the present discussor. This solution has been extended to cover the case of dielectric loss, distributed in the usual manner; the complete equations, covering the case where copper loss, sheath loss, and dielectric loss exist simultaneously, are given below.

In equation (**2**) $W_c$ is the copper loss, $W_s$ the sheath loss, and $W_d$ the dielectric loss, in watts per foot of cable. The definitions of the other quantities are given in the appendix to the aforementioned paper. (TRANS. A.I.E.E., Dec. 1931, page 1420.)

The first term in the square parenthesis in the numerator of equation (**2**) gives the effect of the copper loss; the second term, that of the sheath loss, and the last term, which contains the two integrals, gives the effect of the dielectric loss.

On examining the authors' Fig. 8, it would appear that the error in maximum oil demand introduced by assuming the dielectric loss concentrated on the copper, is not very serious at 132 kv, being of the order of 3 per cent and on the safe side. A more accurate result would probably have been obtained if the dielectric loss had been assumed to be equally divided between the conductor and the sheath. A still more accurate result could be obtained by using equation (**1**) above. The additional complication involved in the use of this equation might be warranted at 230 kv.

The statement is made that, "A small discrepancy between measured and calculated values for the initial part of the oil demand curve is not conclusive evidence of void formation in an oil filled cable as some have maintained." This statement, of course, is correct as it stands, but is nevertheless somewhat misleading. It has never been contended that *any* small discrepancy may be accounted for by void formation. As the authors point out, the discrepancies between the measured and calculated curves may also be due to the following factors:

(a) Errors in the method of calculation, for example

1. The use of approximations such as the graphical evaluation of $C_n$ in the manner described by the authors.
2. The omission of terms in the infinite series, which may be important in the first part of the transient.

(b) Numerical errors in calculations.

(c) Errors in measurement.

(d) Errors due to the use of inaccurate values for the constants of the cable.

(e) Errors due to variations in the "constants" of the cables with temperature, etc.

### COMPLETE EQUATIONS FOR TEMPERATURE TRANSIENTS ON CABLES

$$T = \sum A_n \left[J_o(u_n x) - K_n Y_o(u_n x)\right] \epsilon^{-u_n^2 t/p'q} \tag{1}$$

$$p_{in} = \frac{\dfrac{p'\Delta_1\Delta_2}{\pi}\left[\dfrac{W_c\Delta_1}{u_n r} - W_s\Delta_2 + \dfrac{W_d\,\Delta_1\,\Delta_2}{\log R/r}\left\{\displaystyle\int_r^R \frac{J_o(u_n x)dx}{x} - K_n \int_r^R \frac{Y_o(u_n x)dx}{x}\right\}\right]}{\left[\left\{M_2(u_n R)^2 - N\right\}^2 + (1 + 2M_2)(u_n R)^2\right]\Delta_2^2 + \left[2M_1 - 1 - M_1^2(u_n r)^2\right]\Delta_1^2} \tag{2}$$

The integrals in the numerator have been evaluated in series form, as follows

$$\int \frac{J_o(x)}{x}\, dx = \log x + \sum \frac{(-1)^n (x/2)^{2n}}{2n \cdot n!^2} \tag{3}$$

$$\int \frac{Y_o(x)}{x}\, dx = \frac{\log^2 x}{2} - \sum \frac{(-1)^n (x/2)^{2n}}{2n \cdot n!^2}\left(1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{n} + \frac{1}{2n} - \log x\right) \tag{4}$$

The errors under heading (a) may in general be reduced to a negligible value by the use of the exact mathematical solution and by the use of as many terms of the series as may be needed for the accuracy required. It should be noted that the evaluation of $C_n$ by the method proposed by the authors becomes more and more precise as terms are added to the series.

The numerical errors may be almost entirely eliminated by careful checking. If the value of $C_n$ is calculated mathematically and the temperature as calculated from equation (1), above, is compared with the known limiting condition at time $t = O$, a valuable check on the numerical work is obtained. This check is impractical if the method of calculation of $C_n$ advocated by the authors is used.

With regard to errors in measurement, we appreciate that the authors were working under great difficulties when they tried to obtain reliable field tests on oil demand. Laboratory tests are much easier to control and more accurate data may be expected from such tests. The agreement between test and calculated values as given by the authors in Table II, is very good for a field test. Laboratory tests, however, would probably show even closer agreement.

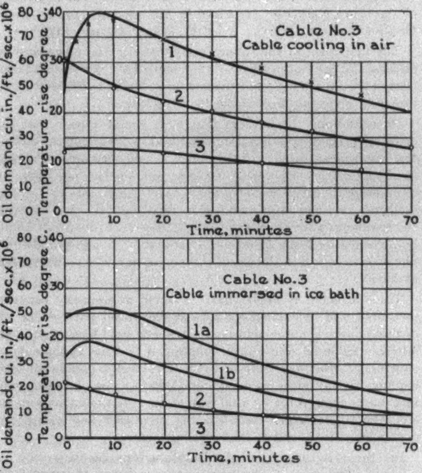

Fig. 2—Oil Demand and Supply After Dropping Load. Theoretical Calculations Shown by Full Line Curves. Test Results Shown by Plotted Points and by Curve 1b in Ice Bath Test

1 —Oil demand and supply
1a—Calculated demand
1b—Measured supply
2 —Copper rise
3 —Sheath rise

The source of errors which is at present the most difficult to eliminate is given under headings (d) and (e). Care is taken in laboratory work to use the constants which apply to the actual cable under test, as far as possible. It is more difficult to determine these constants in the field. Agreement between laboratory tests and calculated values of temperature indicates that the variation of the cable constants with temperature produces comparatively little effect on the transient, excepting in the case of copper resistance. This is well brought out by the authors in their Fig. 1, and by Fig. 2 of this discussion.

In short, if an attempt is made to estimate void formation by comparing a calculation based on assumed constants with a field test, the results would probably not be very accurate. Moreover, it has been brought out that when such an attempt is made it is advisable to use the exact mathematical solution rather than the more approximate graphical solution. It does not necessarily follow, however, that measurements made in the laboratory under properly controlled conditions will not give more satisfactory results.

Fig. 2 in the above-mentioned paper by G. B. Shanklin and F. H. Buller, A.I.E.E. Trans., December 1931, page 1414, shows what can be done in the way of obtaining an exact check between calculated and test values in the laboratory. While the agreement of calculation with test is not perfect in the case of the oil demand curve for cable No. 2, it is on the whole very good. In this case we would certainly hesitate to say that the discrepancies are due to void formation. It should be noted that both cables 1 and 2 were impregnated with a light oil, carefully degasified.

Fig. 2 of this discussion shows two tests on cable 3, which was treated with a heavy oil. A cooling test in air gives a reasonably good check with calculations, indicating that the constants of the cable were known with a good degree of accuracy and did not change materially during the test.

When the same cable is immersed in an ice bath, its temperature is materially reduced and the viscosity of the compound very much increased. The high viscosity of the compound should tend to give rise to void formation. Although there are apparent signs of void formation, there is some question as to whether a discrepancy between tests and calculation is or is not entirely due to void formation in the case where the cable was cooled in air. In our opinion, there is no question but that the discrepancy was due to void formation in the case where the cable was immersed in the ice bath. The agreement between the calculated and measured temperature rises practically excludes the possibility of errors in calculation or of variation of any of the cable constants, with the possible exception of the coefficient of expansion of the compound with temperature. Tests made on this compound indicate that the change in coefficient of expansion over the range considered is not sufficiently large to account for the observed discrepancy. Void formation is the only hypothesis left.

It should be noted that the cable length in this test was short, and was provided with a hollow core. A line in service would have much more serious void formation due to longitudinal pressure drop. Even if a hollow core were used with this type of compound, serious void formation might be expected in service due to longitudinal drop.

Of course, as stated above, the hypothesis of void formation cannot be used to account for any and all discrepancies between observation and calculation. A careful check of both test and calculation and a certain amount of judgment are needed before this hypothesis should even be advanced in any particular case; and in no case should the discrepancy be taken as more than an approximate measure of the amount of void formation likely to occur in a given cable.

However, it is believed that a pronounced discrepancy between calculation and test will almost certainly indicate the existence of void formation under certain conditions.

**Robert J. Wiseman:** The paper by Messrs. Miller and Wollaston is an abstract of a more comprehensive treatise on the subject of thermal transients and pressure gradients in cables. In the past, we have had to consider the design of a cable based on the dielectric strength and dielectric power factor of the insulation. With the improvement in oil and paper as well as manufacturing methods, we have reached a high degree of perfection, but we find now that it is necessary for us to consider more seriously the temperature gradients and the resulting pressure gradients as a cable goes through its loading cycle. This involves the thermal and physical properties of the insulation, hitherto not considered as of great importance, except as limiting the current carrying capacity.

The application of the analysis to both solid and oil-filled, single and multiple conductor cables is most valuable. Researches being carried out by some of the cable manufacturers show internal pressures in solid cable much higher than realized. We have found very high pressures at the conductor and sheath with no indication of a positive pressure in the middle of the insulation. We did not appreciate why this was so. It is very likely that it can be explained by analyzing mathematically along the lines in this paper what should take place. We are now making such a study. It is possible by studying how a cable acts thermally to decide what the physical characteristics of the oil should be in order to prevent excessive internal pressures and, therefore, eliminate the expansion of the lead sheath with its attendant shortcomings.

**K. W. Miller and F. O. Wollaston**: It is a source of considerable satisfaction to us to receive the favorable comment of Messrs. Church, Buller and Wiseman, as well as to know, from private correspondence with individuals who did not discuss our paper, that the methods and charts described by us are proving of practical use to computers, designers, and users of underground cables.

Mr. Church has described a graphical method of obtaining the generalized $L$ function for load curves of any kind whatever and has also suggested the use of a planimeter for this purpose. It may be mentioned here that a very simple mechanical device may be constructed for this purpose from a watthour meter disk and damping magnets, one spring and two pointer arms. When one pointer is made to trace the load curve (plotted in terms of watts loss *vs.* time), then the second arm will automatically draw (to the same scale) the $L_n$ function curve for any selected numerical value of the exponent $\lambda_n$.

Mr. Buller has discussed the convenience and accuracy of the numerical results to be expected from use of our charts and our method of obtaining coefficients $C_n$. An inspection of Charts 1 and 2 indicates that the roots $Z_n$ and hence exponentials $\lambda_n$ will always be very accurately determinable. The first $K_n$ ratio can also be very accurately determined but, for larger roots, $K_n$ decreases in accuracy owing to the points of intersection between curves becoming less definite. However, our simultaneous equation method of solution for coefficients $C_n$ automatically compensates for small inaccuracies in $K_n$ for the curve of initial condition (when $t = O$) and, from the nature of exponentials, the terms involving the largest roots (and $K$ values of greater uncertainty) are the first to shrink to insignificance with increasing time. Briefly stated, mathematically it may be said that the charts for $K_n$ and $Z_n$ and equations for $C_n$ automatically guarantee an accuracy in direct ratio to the importance of the term involved with respect to both space and time.

On physical grounds it may be noted that a small percentage of uncertainty in the thermal constants or cable dimensions will introduce appreciable uncertainty into the $K_n$ values, increasingly so with larger roots, because of the lesser definiteness of the points where the $P$, $Q$ curves intersect, for larger values of $Z_n$, no matter how carefully they may be plotted or computed by formulas. Conversely, for larger roots, increasing changes in $K$ are required for equal physical significance. Intuition or judgment correctly tells one that small changes in the basic (physical) constants cannot have a large effect on the final result and hence these apparently sensitive changes in $K_n$ for large roots are not serious. Therefore, our charts and methods, as well as Mr. Buller's formulas, give substantially the same results as experiments. In view of the fact that the thermal constants of a problem will rarely be known to a certainty beyond the 0 to ±3 per cent accuracy obtainable with our charts, we feel that our methods are sufficiently accurate. For the same reasons, we feel that our method of handling dielectric loss is fully as accurate as the data justify, and very convenient. After all, this is a problem in engineering, not in precision astronomy.

Mr. Buller also raises the question of checking of numerical results. Assuming $M_1$, $M_2$, $N$ and $R/r$ have been correctly determined, this falls naturally into two parts: errors in determining (1) root-ratios $Z_n$, $K_n$, and (2) coefficients $C_n$. In our solution no simple method is available to check the first, but with a little practise one must be very careless to misuse Charts 1 and 2 and checking by repetition is a matter of only a few minutes. For the second part, contrary to Mr. Buller's statement, the $C_n$ values can easily be checked against the curve of initial fit by simple addition. (See Appendix IV, step 6, compared to step 5.) With Mr. Buller's equations, errors will not be discoverable until nearly all the hard work has been completed and the $C_n$ values are obtained and checked against the curve of initial fit. If discrepancies occur, there is in general no way to know where the error was made and one or more mistakes may be very laborious to find and correct when working with such complicated formulas.

With respect to void formation, we do not maintain that differences between computed and experimental curves might not be due in part to void formation, but that, taken alone, this is not a necessary conclusion and that our radial pressure drop calculation enables a more valid conclusion to be reached. We compute the possibility directly rather than as a small difference between two large, somewhat uncertain, values. In this, Mr. Buller apparently agrees, although some statements in previous articles on this point are misleading.

We are pleased to know that Doctor Wiseman is applying the theory outlined to studies of the behavior of compound in cables of the solid insulation type. We have tried to emphasize that the utility of our methods is not limited to cables of the oil-filled type but, on the contrary, a practical analytical method is now available enabling engineers to attack successfully some of the problems of void formation and migration and pressures of compound in solid type cables.

# Voltage Regulation of Cables Used for Low-Voltage A-C. Distribution

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Fellow, A.I.E.E.

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It is generally recognized that the design of a distribution system for alternating current at low voltages does not depend primarily upon the selection of a conductor size which shall be thermally sufficient to carry the load, but depends upon the voltage regulation limits which will be satisfactory for lighting especially when combined light and power loads are carried on the same circuit.

The increment starting currents of induction motors are not only large compared to the running current but are of low power factor as well. In order to avoid flicker in illumination where light and power loads are combined, it is necessary to keep the circuit reactance to a consistent minimum in order to minimize the effect of increment motor starting currents of low power factor.

Improved voltage regulation of power circuits will also result in economies due to the relations which exist between voltage and torque in the induction motor. This is particularly true where torque is the application limitation as with elevators and printing machinery.

Voltage regulation by definition is the ratio of the difference between the impressed voltage and received voltage to the received voltage expressed as a percentage and thus for any circuit carrying alternating current it becomes a function of the magnitude of the current, the power factor, and the circuit impedance. Only the first of these factors approximates a simple linear relation to the voltage regulation.

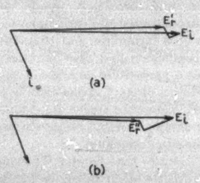

Fig. 1—Comparative Vector Diagrams

Showing resulting voltage drops with low and high reactance circuits at a low power factor load

Circuits which contain the larger values of inductance give poorer voltage regulation with low power factor currents because the inductive voltage drop is more nearly in phase with the line voltage. This may be readily noted in the comparative vector diagrams shown in Fig. 1 where (*a*) shows the resulting voltage regulation obtained with a circuit having a small value of reactance and (*b*) that obtained with a circuit having approximately three times the reactance of the former circuit.

The current carrying capacity of a conductor is usually thought of in terms of its physical size but this physical size is an index to only one of the components of its impedance and thus in itself does not furnish any simple picture of what may be expected in voltage regulation in the general case.

If consideration were given only to regulation at unity power factor, then the physical size of the conductor would furnish an index of the inverse proportionality between voltage regulation per unit length and increasing sizes of conductors. However, if load currents of lower and lower lagging power factors are applied it soon becomes apparent that the inductance component of the impedance becomes the major parameter affecting the voltage regulation.

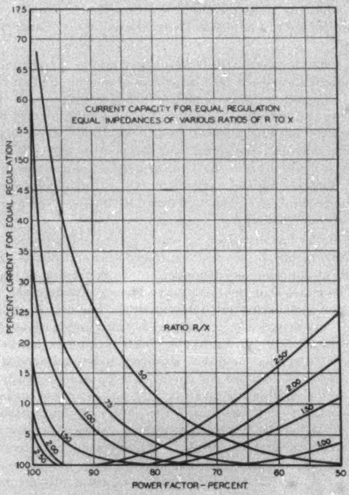

Fig. 2—Ratio of Load Current at Various Power Factors to Minimum Current

To give equal values of voltage regulation with equal circuit impedances for various ratios of *R* to *X*

If a choice of circuits constants be made, such that certain ratios of resistance to reactance obtain, it is possible to produce quite different trend curves of voltage regulation. Considering a constant value of voltage regulation for circuits having equal values of impedance, the ratio of current at any power factor to the minimum current giving that value of regulation may be calculated for various ratios of resistance to reactance. (See Appendix I.) Such a set of data is shown graphically in Fig. 2.

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*The New York Edison Co. and The United Electric Light & Power Company.

†The United Electric Light & Power Co.

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It will be noted that if the ratio of resistance to reactance is less than unity the per cent current which may be carried to give equal values of regulation decreases very rapidly with decreasing power factor. On the other hand, if a relatively large ratio of resistance to reactance is selected, the current becomes an increasing function for equal regulation at the lower power factors. Thus, if a choice could readily be made, it would seem desirable to choose a ratio of resistance to reactance of something between 1.5 and 2.0 for a circuit which would be subject to variable lagging power factor loadings as ratios near these values tend to give more nearly uniform voltage regulation over a range of power factors from 50 to 100 per cent. In applying such a selection of ratios of resistance to reactance to the design of alternating current circuit, one is immediately faced with the problem that while the resistance per unit length of the circuit is variable depending only on the physical size of the conductor, the reactance per unit length of the given circuit is almost independent of the physical size of the conductors and for a single circuit with cables can only be changed by changes in cable construction. Thus in order to obtain a certain optimum ratio of resistance to reactance for a circuit, there are in general, three courses of attack; first, for a given physical size, the reactance component may be changed by changing the cable construction (single conductor or multi-conductor cables with sector type or concentric type construction), second, by changes in the physical size of the conductor, and third, by paralleling two or more circuits.

### Concentric Cables

Concentric cable construction has long been used for feeders on low-tension d-c. distribution because of the space factor consideration. For three-phase a-c. distribution this type of construction applied to three conductors instead of two gives the minimum reactance per unit length which it is possible to obtain with a single circuit for a fixed value of insulation thickness. In addition, this construction gives a very flat regulation curve for physical conductor sizes which would be commonly used for distribution purposes, that is, sizes from No. 4/0 to 500,000-cir. mils. The construction, however, does not lend itself readily to permit splicing operations to be made while the cable is alive, therefore, while this type of construction might prove very satisfactory for radial feeders to individual motors, it would not be practical for use in making up a secondary network grid.

### Sector Cable, Three-Conductor

Three-conductor sector cable provides, by constructional features, the next higher reactance per unit length for single circuits. Its use again is subject to the same limitations as for the concentric type construction in that splicing operations cannot be made readily while the cable is alive.

### Single-Conductor Cable

Single-conductor cables have the highest reactance per unit of length of all the types of cable construction in commercial use due to the increased spacings which result between conductors. While the disadvantage of the relatively high reactance component has long been realized this type has found almost universal favor in the construction of alternating current mains because of practical splicing considerations. If it were desired to obtain a relatively flat regulation curve with a single circuit of single-conductor cable, it would be necessary to use rather small physical sizes in order that the optimum ratio of resistance to reactance be maintained.

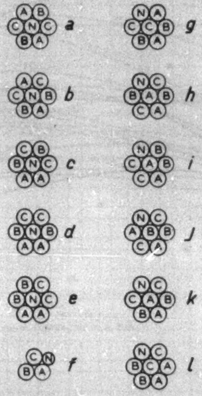

Fig. 3—Phase Conductor Positions for Various Twin Circuit Arrangements

### Multi-Circuits of Single-Conductor Cables

Since information on single-conductor cable indicates that good regulation would obtain over a considerable range of power factor only with the use of small physical sizes, it would of course become obvious that several circuits of the smaller size cables could be paralleled thereby maintaining the same ratio of resistance to reactance while obtaining the actual values of resistance to provide sufficient current carrying capacity. However, when two or more circuits are placed in close proximity the reactance of the parallel circuit is made up not only of the self-inductance of the circuit but also of the mutual inductance between the circuits. By altering the physical arrangements of conductors in a twin circuit for three-phase distribution made up of six conductors it is possible to have the mutual inductance become either additive or subtractive from the self-inductance of each circuit. This results in the overall reactance of the circuit being either somewhat greater or somewhat less than one-half the reactance of a single circuit. Formulas are given in the appendix for calculating the various arrangements.

The voltage regulation which obtains with twin circuits depends in part also on the mutual phase relations which exist between the several conductors. These various arrangements are shown in Fig. 3. The arrangement (*a*) results in the minimum voltage regulation and arrangement (*e*) in the maximum voltage regulation. A comparison of the voltage regulation which obtains with these two limiting arrangements of twin circuits of No. 4/0 single-conductor cables and with a single circuit of 500,000-cir. mil single-conductor cable carrying the same load current, 400 amperes, is shown in Fig. 4.

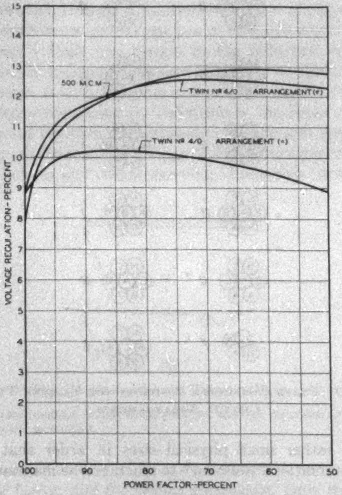

Fig. 4—Voltage Regulation per Thousand Circuit Feet with Load Current of 400 Amperes

For two arrangements of twin circuits of No. 4/0 cable and for a single circuit of 500,000-cir. mil cable

## Test Results with Single Circuits and Twin Circuits Made Up with Single-Conductor Cable

In order to check the differences which a theoretical study indicated to exist between single circuits and twin circuits of single-conductor cable a test set-up was made with 500 circuit feet of 3 single-conductor cables of 500,000-cir. mil and No. 4/0 neutral for the single circuit and 500 circuit feet of 7 single-conductor cables of No. 4/0 size for the twin circuit arrangements.

TABLE I

| Arrangement | Impedance Calculated R | 10⁻⁶ ohms/ft. Calculated X | Measured R | Measured X | Measured percent unbalance in current between conductors |
|---|---|---|---|---|---|
| a | 25.70 | 15.79 | 25.76 | 16.96 | 2.0 |
| b | 25.70 | 17.60 | 28.10 | 17.76 | 14.8 |
| c | 25.70 | 21.50 | 27.16 | 23.04 | 13.0 |
| d | 25.70 | 23.90 | 29.16 | 24.20 | 1.6 |
| e | 25.70 | 27.74 | 30.40 | 28.18 | 14.8 |
| f* | 22.80 | 31.20 | 25.22 | 32.16 | |
| g | | | 28.60 | 17.74 | 10.1 |
| h | | | 27.12 | 17.48 | 6.0 |
| i | | | 29.80 | 24.80 | 5.6 |
| j | | | 28.96 | 18.00 | 13.8 |
| k | | | 27.22 | 18.28 | 5.8 |
| l | | | 29.72 | 24.42 | 12.7 |

*Arrangement (f) is single circuit of 3 single-conductor 500,000-cir. mil cables and a 4/0 neutral.

All the other arrangements are twin circuits of 6 single-conductor 4/0 cables and a 4/0 neutral.

Various groupings of phase relations were measured in the several arrangements as indicated in Fig. 3 in order to check the calculated constants.

Test results indicated agreement with the calculated values within the precision of measurements used in the test and are summarized in Table I. It will be noted that there is an effective increase in the resistance of the conductors in single-conductor lead sheathed cable due to sheath losses and these are not entirely negligible in the larger sizes of cable even when the 3 cables are mutually tangent. These sheath losses give an apparent increase in conductor resistance of 5.5 per cent for 500,000-cir. mil single-conductor cables, 2.3 per cent for 350,000-cir. mil single-conductor cables and 0.7 per cent for No. 4/0 single-conductor cables.

## Spaced Conductors

From the foregoing, it follows that busses and separated conductors (such as are generally used in temporary construction service) have inherently high reactance. The use of these configurations should be avoided where good voltage regulation is required unless the circuit length is short.

## Regulation Efficiency

The regulation efficiency, that is, the amperes per thousand circular mil, which may be carried in a given cable to give one per cent voltage regulation per 100 circuit feet on a three-phase four-wire 120/208 volt circuit for the various types of construction and sizes of cable is shown in Fig. 5. It will be noted for any given type of cable construction that the regulation efficiency improves with the smaller wire sizes of cable, and that by types of cable construction, the concentric type has the greatest efficiency, the sector type the next better efficiency and single conductor the poorest efficiency, with the twin circuits of single-conductor cable lying between the values for single-conductor cable and sector type of cable.

While the concentric type of cable construction has the highest regulation efficiency, it is also the most expensive. Based upon manufacturers' figures (market value of copper and lead being 6 cents and 3 cents respectively), the following table indicates the relative cost for the various sizes and type of cables where 1/0 single-conductor rubber insulated lead sheathed cable has been taken as the base at 100 per cent.

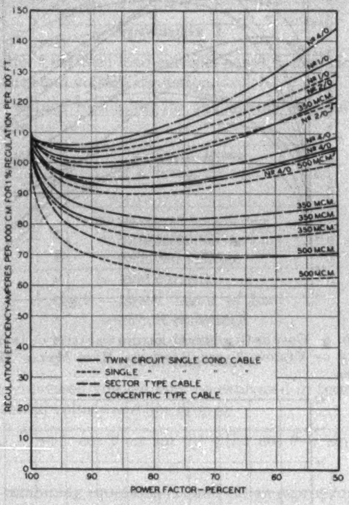

FIG. 5—REGULATION EFFICIENCY OF VARIOUS TYPES OF CABLE

RELATIVE COSTS OF CABLE IN PER CENT PER UNIT CIRCUIT LENGTH

| Cable size | *Single cond. cable (3 cables) | †Sector cable | †Concentric cable |
|---|---|---|---|
| 1/0 | 100 | 148 | 181 |
| 2/0 | 116 | 173 | 213 |
| 4/0 | 140 | 243 | 262 |
| 350,000 cir. mil | 221 | 365 | 360 |
| 500,000 cir. mil | 300 | 470 | 455 |

*Low-tension cable rubber-insulated lead sheathed.
†Low-tension cable 3-conductor paper-insulated lead sheathed.

Combining the data of the regulation efficiency and the cost of cable, trend curves are obtained which show the cost per unit of carrying capacity for unit regulation with various power factors. These curves are shown in Fig. 6. These data indicate that there is a spread of some 85 per cent in cost for the various cable sizes usually found in practise to give the same regulation per unit length of circuit.

## COST OF CABLES INSTALLED

The previous cost data includes only the cost of cable, but the true economic study of relative cost should be based on cables installed and spliced particularly where the installation cost may be somewhat different for the different types of cable construction and arrangement. Based upon field studies it is indicated that the pulling in charges for twin circuits, six single-conductor cables and neutral, in the same duct is about 10 per cent greater than the charges for four single-conductor cables or for a multi-conductor cable.

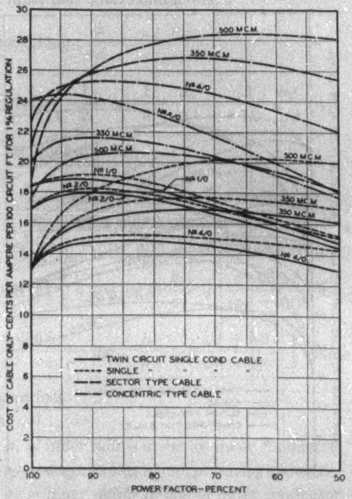

FIG. 6—COST OF CURRENT CARRYING CAPACITY OF VARIOUS TYPES OF CABLE

The relative costs of splicing single circuits of single-conductor cable and multi-conductor cable are as follows:

| Cable size | Relative cost of splicing in per cent |
|---|---|
| 1/0 | 100 |
| 2/0 | 111 |
| 4/0 | 122 |
| 350,000 cir. mil | 132 |
| 500,000 cir. mil | 140 |

Field studies on the splicing of twin circuits indicated that this cost was about 50 per cent greater than for the splicing of single circuits.

With the cost of installing and splicing cable added to the cost of the cable a new set of trend curves is obtained which shows the total cost per unit circuit length to give equal regulation at various power factors. See Fig. 7.

It is also of interest to know to what extent the variations in the metal market may be reflected in the cost of regulation of the various types and sizes of cable. A set of curves has been prepared in Fig. 8 showing this cost based on copper and lead prices of 18 cents and 6½ cents per lb. respectively.

## CONCLUSIONS

The economic comparisons as indicated in Figs. 7 and 8 show that with low metal market prices twin circuits with No. 4/0 single-conductor cables provide the most economical distribution unit. At relatively high metal market prices both 350,000-cir. mil and 500,000-cir. mil concentric type cable show a slightly lower cost than twin circuit of No. 4/0 cables. While these concentric type cables might prove adaptable to construction which is not required to be worked alive it appears that for low-tension mains cable the twin circuits of No. 4/0 cable hold an economic advantage whether the metal market be high or low.

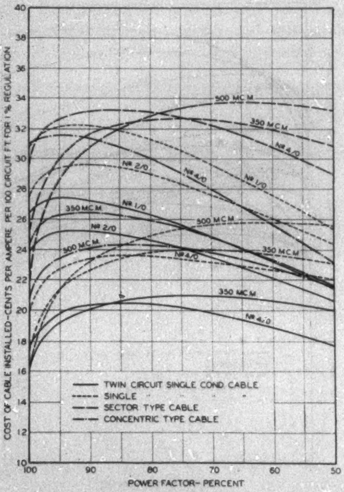

FIG. 7—COST OF CURRENT CARRYING CAPACITY OF INSTALLED CABLE OF VARIOUS TYPES BASED ON LOW METAL MARKET PRICES

Field experience has indicated that it is practical to keep relative phase arrangements during pulling in and splicing of the cable and thereby are able to secure the maximum economic use of the twin circuit main. The comparative cost of installed cable between the most favorable and least favorable arrangement of twin circuits of No. 4/0 cable and a single circuit of 500,000-cir. mil cable is shown in Fig. 9. Actual investment per circuit foot is substantially the same for either of

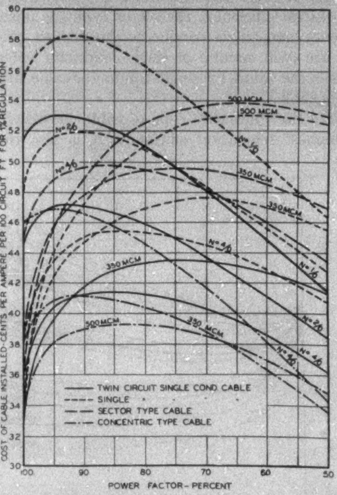

FIG. 8—COST OF CURRENT CARRYING CAPACITY OF INSTALLED CABLE OF VARIOUS TYPES BASED ON HIGH METAL MARKET PRICES

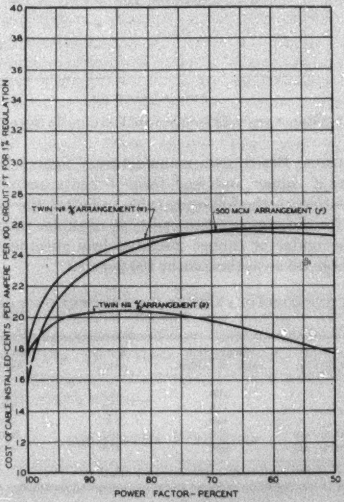

FIG. 9—EFFECT OF PHASE ARRANGEMENTS ON THE COST OF CURRENT CARRYING CAPACITY

these two types of construction. It will be noted that at low power factor even the most unfavorable arrangement of twin circuits is preferable to a single circuit.

In all the theoretical material included in this paper the reactance values used have been calculated on assuming the cables to lie mutually tangent. This condition has been found to hold to a fair degree of approximation in the case of twin circuits installed in a common duct but single circuits usually show an appreciable increase in reactance over the calculated values for close spacing due to their spreading out in the duct.

## Appendix I

Relations between load current, power factor, circuit impedance and voltage regulation.

The voltage regulation for any circuit may be expressed as

$$\gamma = \frac{E_i - E_r}{E_r} \tag{1}$$

where

$E_i$ = impressed voltage
$E_r$ = received voltage
$i$ = load current
$\cos\theta$ = power factor of load
$r$ = circuit resistance
$x$ = circuit reactance
$z$ = circuit impedance

The impressed voltage may be expressed in terms of the received voltage and line drop as

$$E_i = \sqrt{[E_r + i(r\cos\theta + x\sin\theta)]^2 + [i(x\cos\theta - r\sin\theta)]^2} \tag{2}$$

By combining equations (**1**) and (**2**) an expression for load current is obtained in terms of voltage, power factor, impedance and regulation

$$i = \frac{E_r\left\{\sqrt{(r\cos\theta + x\sin\theta)^2 + z^2[(1+\gamma)^2 - 1]} - (r\cos\theta + x\sin\theta)\right\}}{z^2} \tag{3}$$

The minimum load current ($i_{min}$) which obtains for a given value of voltage regulation is at a power factor such that $\theta = \tan^{-1} x/r$ and may be expressed as

$$i_{min} = \frac{E_r\,\gamma}{z} \tag{4}$$

By combining equations (**3**) and (**4**) an expression for the ratio of load currents is obtained as a function of load power factor, circuit impedance and voltage regulation

$$i/i_{min} = \frac{\sqrt{(r\cos\theta + x\sin\theta)^2 + z^2[(1+\gamma)^2 - 1]} - (r\cos\theta + x\sin\theta)}{z\gamma} \tag{5}$$

## Appendix II

### 60-Cycle Reactance of Cable

1. The reactance per conductor of 3 single conductors carrying balanced three-phase currents, for equal spacing, is

$$x = 0.0529\log_{10}\frac{s}{a} + 0.00574 \text{ ohms per thousand feet}$$

where

$a$ = radius of conductor
$s$ = distance between centers of conductors

2. The reactance per conductor of triple concentric cable for this study was taken as the average of values obtained from the following:

(a) Between inner and center conductors and between inner and outer conductors.

$$x = 0.0529\log_{10}\frac{b_1}{a_2} + 0.0115\left(\frac{1}{2} + \frac{1}{3}\frac{a_2^2}{b_1^2} - \frac{1}{12}\frac{a_2^4}{b_1^4} + \dots\right)$$

ohms per thousand feet

where

$a_2$ = outer radius of inner conductor
$b_1$ = inner radius of outer conductor

(b) Between center and outer conductors.

$$x = 0.01151\left[4.606\log_{10}\frac{b_1}{a_2} + \frac{4.606\,a_1^4}{(a_2^2 - a_1^2)^2}\log_{10}\frac{a_2}{a_1} + \frac{4.606\,b_2^4}{(a_2^2 - a_1^2)^2}\log_{10}\frac{b_2}{b_1} - \frac{a_1^2 + b_2^2}{a_2^2 - a_1^2}\right] \text{ ohms per thousand feet}$$

where

$a_1$ = inner radius in cm. of inner conductor
$a_2$ = outer radius in cm. of inner conductor
$b_1$ = inner radius in cm. of outer conductor
$b_2$ = outer radius in cm. of outer conductor

3. Reactance of twin circuits—while numerous arrangements of twin circuits are possible as has been indicated in Fig. 3 formulas are only included for the first five cases as these cover all the possible arrangements when the neutral conductor is maintained in the central position of the group.

Referring to Fig. 10 it will be noted that the conductors have been given numbers in order to simplify the subscript designation and each of the following equations gives the average 60-cycle reactance for the individual conductors. The following symbols are used

$a$ = radius of conductor
$S_{12}$ = distance between centers of conductors 1 and 2
$S_{13}$ = distance between centers of conductors 1 and 3 etc.

(a) Reactance of arrangement shown in Fig. 3a

$$x = 0.01149 \left[ 0.5 + 4.606 \log_{10} \frac{(S_{12}S_{23}S_{31})^{1/3}(S_{51}S_{61}S_{42}S_{62}S_{43}S_{53})^{1/6}}{a\,(S_{41}S_{52}S_{63})^{1/3}} \right]$$

$$= 0.0529 \log_{10} \frac{\sqrt{3}\,S_{12}}{2a} + 0.00574 \text{ ohms per thousand feet.}$$

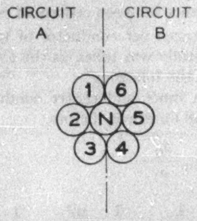

Fig. 10

(b) Similarly the reactance of arrangement shown in Fig. 3b

$$x = 0.0529 \log_{10} \frac{S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(c) Reactance of arrangement shown in Fig. 3c

$$x = 0.0529 \log_{10} \frac{\sqrt{2}\,S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(d) Reactance of arrangement shown in Fig. 3d

$$x = 0.0529 \log_{10} \frac{\sqrt{3}\,S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(e) Reactance of arrangement shown in Fig. 3c

$$x = 0.0529 \log_{10} \frac{\sqrt{2}\ \sqrt{3}\ S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

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1. "The Theory of Alternating Currents," Alexander Russell, Vol. I, Second Edition, Chap. 2.

2. "Electrical Characteristics of Transmission Circuits," William Nesbit.

3. "The Impedance and Power Losses of Three-Phase Overhead Lines," P. D. Morgan and S. Whitehead. *Jl. of I.E.E.*, Vol. 68, p. 367, 1930.

# Traveling-Wave Voltages in Cables

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***Synopsis.***—*The problem of lightning protection of cables is more active at the present time than it has been in the past. This is due largely to the fact that cables of higher voltage connected directly to overhead lines are becoming very common; cables in the form of short sections are especially liable to need protection. The cost of the cable, the importance of the line from the operating standpoint, and the cost of protective equipment all enter into the picture.*

*In the present paper the factors which determine whether or not a cable will require protective equipment are discussed, and new and simplified formulas, representing with considerable precision any of the standard coordinating waves are developed. These formulas can be used for open-ended cable lines, or cable sections in transmission lines. Where cables terminate in station apparatus, the assumption of an open-circuited cable end may be safely used, since it always gives a calculated value of voltage that is somewhat above the true value. The effect of cable length and surge impedance and of line surge impedance are illustrated in detail. Tentative data on the impulse strength of cable insulation are also included.*

## INTRODUCTORY

In the earlier days of the electrical industry, comparatively little attention was paid to the protection of cables against lightning surges. Where cable lines were not connected to overhead lines, or where they were connected to such lines through transformers, special devices for the protection of cables were unnecessary, since the lightning surges impressed on such cables were seldom if ever of great severity. Furthermore, the high impulse ratio of cable insulation, together with the inherent tendency of cables, especially long ones, to reduce the magnitude of an entering wave to a relatively low value, has tended to make cables self-protecting. These factors still make protection unnecessary in many cases.

During the last decade, however, the maximum voltage at which cables have been successfully operated in commercial service has steadily increased; and there is reason to believe that this voltage will increase yet further in the future. This fact has resulted in an increasing use of short cable sections on high tension transmission lines; both at the end of a line, where overhead transmission is often impractical, and at points along the length of a line. Such links, being short, are not necessarily self-protecting. Again, the great advances made during this period in the art of cable manufacture have resulted in a considerable increase in the life of cables, and in their dielectric strength at operating frequencies; this improvement has been greater than the corresponding improvement in impulse strength. Finally, the cost of a high-voltage cable section is by no means negligible, and its importance from the operating standpoint is usually very great.

On the other hand, the cost of high-voltage protective equipment is often an appreciable item in the total cost of the cable section or cable line. It becomes increasingly important, therefore, to determine with some precision just when such equipment is required, and when it can safely be dispensed with.

The movement for the coordination of insulation which is at present on foot makes it particularly desirable to insure that a cable shall not prove to be a weak link in a system. It is because of this movement that formulas have been developed in terms of exponential wave shapes which approximate closely to the actual shapes of the coordinating waves. These formulas, incidentally, afford a method of calculation which is very much simpler than the "step-by-step" method usually used for such work.[‡] Moreover, calculations can be made by these formulas in a much shorter time.

The factors which determine whether a cable needs lightning protection or not are as follows:

a. The magnitude of the incoming wave. This is usually limited by the impulse flashover of the line insulation or cable terminal, or possibly by a coordinating gap.

b. The effect of the cable and line surge impedances on the traveling wave.

c. The effect of the impedance at the far end of the cable.

d. The length of the cable, and its dielectric constant.

e. The impulse strength of the cable.

These last four factors are discussed in more detail in the following paragraphs.

## EFFECT OF THE CABLE ON THE TRAVELING WAVE

When a traveling wave on an overhead line reaches a cable, a wave of reduced voltage passes into the cable. This reduction is due to the fact that the surge impedance of a cable is less than that of an overhead line.

In a traveling wave the electrostatic energy is equal to the electromagnetic energy and the constants of a cable are such that the voltage of a traveling wave has a lower ratio to the current than in the case of a wave on an overhead line. After the wave enters the cable there are voltage and current reflections back and forth from each terminal. If the length of the original wave is great enough there will be several superimposed waves at each point in the cable. The sum of these several waves will be dependent upon the shape of the

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

[‡] The "step-by-step" method is successfully used by Beck (Bibliography, reference 1) and other writers.

original wave as well as the reflection from each end of the cable.

The reflection at the cable terminal depends upon the surge impedances of the cable and of the connected line or apparatus. In this paper, calculated values of voltage are given for a range of cable surge impedance from 20 to 150 ohms and line impedances of 300 and 500 ohms. The calculations include the case of similar lines connected to each end of the cable, and the case of a line connected to one end of the cable only and a free terminal at the other, which is the case giving the highest voltage. The traveling wave is assumed to enter at the "near" end of the cable and the voltage at the "far" end calculated, since in general the maximum voltage will be found at that end. Reduction of the wave by cable losses was neglected, as tests have shown the losses to be small in 500- and 1,000-foot lengths of cable.

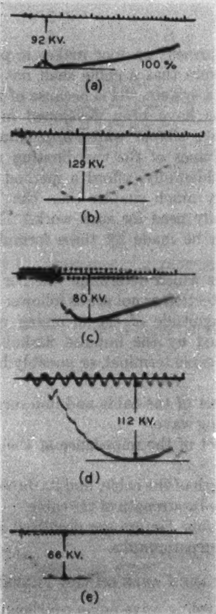

Fig. 1—Oscillograms of Traveling Wave Voltages Measured at "Far" End of Cable

(a) Line wave
(b) "Far" end of 500-ft. cable open at "far" end
(c) "Far" end of 500-ft. cable between two lines
(d) "Far" end of 1,000-ft. cable open at "far" end
(e) "Far" end of 1,000-ft. cable between two lines

## Typical Waves Used in Calculations

Three different waves have been used in various coordination studies. They are the ½-5, the 1-10 and the 1½-40, in which the first figure is the time in microseconds to reach crest, and the second figure the time to reach half value on the tail of the wave. However, since both tests and calculation show that short wave fronts do not greatly affect the ultimate voltage resulting in the cable, and since turn-to-turn stresses in apparatus due to steep wave fronts are not being considered here the mathematical treatment of the problem in this paper has been simplified by using the 0-5, 0-10 and 0-40 waves. The waves have respectively the following formulas: $E\epsilon^{-.138t}$, $E\epsilon^{-.0692t}$ and $E\epsilon^{-.0173t}$, and will give slightly higher values for ultimate cable voltage than would be obtained from the first mentioned waves.

With these waves entering the cable the voltage at the cable terminals will rise to its maximum value and then decrease in a series of steps by successive reflections, each step having a vertical front. Under these conditions, it is possible to derive a simple formula for the maximum voltage at either cable terminal for the $n$th step, and also to determine the step at which the voltage will be a maximum (Fig. 6). This method was used because the principal interest in this paper is the maximum value to which the voltage rises in the cable rather than its rate of rise. (See Appendix I.)

## Comparison with Field Tests

Results obtained by the above method check closely the field measurements obtained by Messrs. McEachron, Hemstreet and Seelye, in the Michigan tests on cables.[2] Oscillographic measurements from the Michigan tests are shown in Fig. 1. The following table gives the relation between the calculated and measured values for approximately the same conditions. The line surge impedance was 500 ohms, the cable impedance 50 ohms and a 2-50 wave arriving over the line.

TABLE I

| | Measured | Calculated |
|---|---|---|
| Line to 500 ft. cable open at far end | 142% | 150% |
| Line to 1,000 ft. cable open at far end | 120% | 124% |
| Line to 500 ft. cable to line | 87% | 82% |
| Line to 1,000 ft. cable to line | 72% | 74% |

## Effect of Wave Shape

As pointed out, the voltage resulting in the cable is dependent on the shape of the incident wave. This is shown in Fig. 2 where voltages at the "far" end resulting from the three waves are plotted for lengths of cable up to 20 microseconds.* The line impedance was taken as 500 ohms and the cable impedance 50 ohms. The "near" terminal of the cable is connected to the overhead line and the "far" terminal is free, *i.e.*, having no electrical connections. To make the curves general, the cable length is plotted in microseconds since the wave propagation velocity varies in different cables. The length of the cable in microseconds is approximately equal to the cable length in thousands of ft. multiplied by $\sqrt{K}$, the sq. root of dielectric constant of the cable insulation. This relation is due to the fact that the propagation velocity of electric waves is inversely proportional to the sq. root of the permittivity or dielectric constant of the insulating medium.

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[2] For numbered references see Bibliography.

*See Appendix II.

It may be noted (Fig. 2) that cable voltage is greater for the waves which decrease more slowly with time. This difference is more pronounced for the shorter lengths of cables. For example, in a two-microsecond cable which might be approximately 1,100 ft. in length, a 0-40 wave rises to 117 per cent, a 0-10 wave rises to 72 per cent and a 0-5 wave rises to 54 per cent. These values are referred to the crest of the incident wave or original wave arriving over the line, which is 100 per cent.

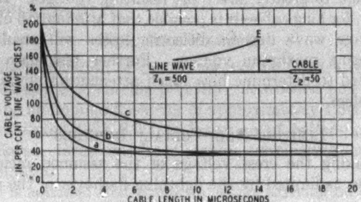

FIG. 2—MAXIMUM VOLTAGE AT "FAR" END OF CABLE

Resulting from (*a*) 0-5, (*b*) 0-10 and (*c*) 0-40 line waves. Cable open at "far" end

Although the curves cover a range of lengths up to 20 microseconds only, it should be noted further that where the cable is sufficiently long the voltage at the "far" end is equal to the first entering wave plus its reflection, the effect of further reflections being negligible. Since in this case the terminal at the "far" end of the cable is disconnected, the minimum value of voltage is twice the first entering wave.

### EFFECT OF LINE SURGE IMPEDANCE

To show how surge impedance of the line affects the cable voltage, curves are given for two values of line impedance, 300 and 500 ohms, with the 0-40 wave and 50-ohm cable impedance as shown in Fig. 3. These curves show that a higher surge impedance of the line results in a lower voltage in the cable. The effect is greater with longer cables.

### EFFECT OF CABLE SURGE IMPEDANCE

Fig. 4 shows how cable surge impedance affects the resulting voltage. In this case the cable impedance was varied from 20 to 150 ohms while the other factors were kept constant. In practise the cable surge impedance varies over a relatively greater range than the line impedance. These curves show a wide difference of cable voltage for the eight values of cable surge impedance examined. For example, with an 8-microsecond cable, the voltage varies from 40 per cent to about 120 per cent for impedances of 20 and 150 ohms respectively.

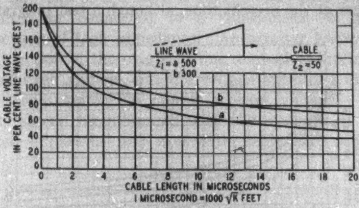

FIG. 3—MAXIMUM VOLTAGE AT "FAR" END OF CABLE

Resulting from a 0-40 wave on lines of 300 and 500 ohms surge impedance Cable open at "far" end

### EFFECT OF IMPEDANCE AT "FAR" END OF CABLE

Where a line is connected at the "far" end of the cable, as shown in Fig. 5, the reflected voltage, and therefore the resultant voltage, is less than that for an open-end cable where full reflection occurs. This may be seen by comparing the curves in Fig. 5 with the corresponding curves in Fig. 4. Take the case of a 20-microsecond cable of 30 ohms surge impedance, the voltage is about 33 per cent in Fig. 4 and about 28 per cent in Fig. 5. This difference is small. But if the cable length is decreased to 2 microseconds, the cable voltage is about 97 per cent in Fig. 4 and nearly 63 per cent in Fig. 5. These curves show that the impedance connected at the "far" end of the cable is more important in the case of shorter cables. As the cable length approaches zero, the cable voltage approaches 100 per cent in Fig. 5 where the "far" end of the cable is connected to a line, and 200 per cent in Fig. 4 where the "far" end of the cable is an open circuit. When

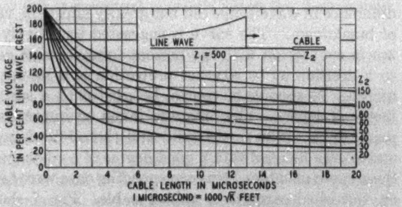

FIG. 4—MAXIMUM VOLTAGE AT "FAR" END OF CABLES OF VARIOUS SURGE IMPEDANCES

Resulting from a 0-40 wave on a line of 500 ohms surge impedance. Cable open at "far" end apparatus is connected to the "far" end of the cable and has a high impedance compared with the cable, the condition is approximately that of open circuit at the "far" end. This assumption always gives a value of voltage in the cable which is slightly higher than the value which actually will occur where the cable terminates in station apparatus.*

### IMPULSE STRENGTHS

Data on the impulse strength of cables are very meager at the present time, although a test program is under way which should go far in extending the knowledge now available. The curve given in Fig. 7 is based on somewhat limited data, taken with the three coordinating waves previously referred to. The curve actually represents an average value of all the data obtained, since it appeared from the tests that the difference in wave shape did not greatly affect the value of breakdown. The curve is suggested tentatively for use in connection with the present formulas as a guide to a decision as to whether protection is or is not required. It should, of course, be used with a suitable factor of safety. The data was taken on impregnated paper cable, of both the solid and the oil-filled types; and it may be used with a good degree of confidence for these types of cables. No corresponding data were taken on varnished cambric or rubber cable. Fig. 7 should therefore be used with great caution when considering these types of cable.

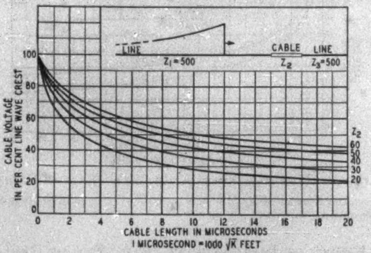

FIG. 5—MAXIMUM VOLTAGE AT "FAR" END OF CABLES OF VARIOUS SURGE IMPEDANCES

Resulting from a 0-40 wave on a line of 500 ohms surge impedance. Cable connected between two lines

Tables giving line flashover values for various numbers of standard 5¾ by 10 in. disk insulators have been published in a number of places by F. W. Peek, Jr.[3,4] The impulse strength of wood pole lines may be estimated from the length of wood in circuit to ground.[5,6]

### CABLE SURGE IMPEDANCE

The surge impedance of the cable can be determined from the formula.

$$Z \text{ (cable)} = \frac{G}{0.0169\, n\sqrt{K}}$$

Where

$K$ = dielectric constant of cable insulation.
$n$ = number of conductors.
$G$ = geometric factor.

Curves of $G$ have been published in several places by Simmons.[6,10] Table II gives working values for the cable dielectric constant.

TABLE II

| Type of insulation | Working value of $K$ |
|---|---|
| Paper (solid) | 3.5 |
| Paper (oil filled) | 3.4 |
| Varnished cambric | 4.2 |
| Rubber | 4.4 |

Dielectric losses in the cable were neglected when preparing the curves. Results from the Michigan tests indicate that for short cables this loss is not great enough to greatly affect the resulting voltages. However, for long cables it is possible that attenuation of the voltage wave due to dielectric losses will result in lowering maximum voltage. Further test data are needed to determine how much attenuation alters the problem.

### LIMITING HIGH VOLTAGE IMPULSES

Taking the crest voltage of the assumed incident waves as limited by the lightning flashover of the connected line, these curves and formulas may be used to determine the maximum voltage to which a cable and connected apparatus will be subjected. This value can be compared with the insulation strength of the cable, pothead, and connected apparatus to determine the protective requirements.

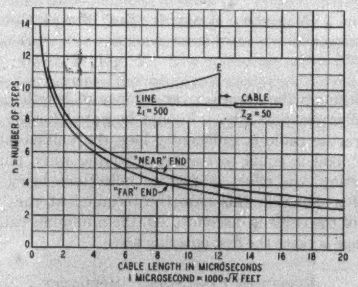

FIG. 6—NUMBER OF STEPS TO REACH MAXIMUM VOLTAGE AT ENDS OF CABLE AS FUNCTION OF CABLE LENGTH

Cable open at "far" end

Where a cable of comparatively low voltage rating and correspondingly low impulse strength is connected to a wood pole line having high insulation level, the application of lightning arresters at the junction of cable and line becomes especially important, since without an arrester the first transmitted wave in the cable may exceed the cable strength. Assuming that the wave entering the cable is thus limited by an arrester at the line end of the cable, it may still be necessary to use an arrester at the "far" end of the cable to prevent further rise of voltage by reflection, particularly if connected apparatus at the "far" end would not withstand reflection (approaching double value) of the voltage wave passed by the arrester at the junction of cable and line.

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*The matter of terminal impedances has been covered in more detail by Bewley. See Bibliography 12.

For shorter lengths of cables where several reflections occur in the cable before reaching a maximum value, the crest value of voltage will be approximately the same at both ends of the cable. Under such conditions the application of a single arrester may be sufficient protection. Where there is apparatus at the "far" end of the cable, location of the arrester at that end will conform to the general recommendation that the arrester be located within 50 circuit feet of the apparatus for circuits below 69 kv. and within 100 circuit feet for circuits above 69 kv.

## PRACTICAL EXAMPLE

The application of the curves can be illustrated by calculation of a specific problem. A wooden pole line having an impulse flashover of approximately 1,500 kv. is connected to a 2,000-foot section of belted-paper-insulated three-conductor cable terminating in a substation.

It is assumed that equal waves are arriving on each conductor of 1,500 kv. Under these conditions the surge impedance of each line is taken as 500 ohms. The cable has the following characteristics:

| | |
|---|---|
| Paper insulation thickness: | |
| a. Between conductors | 0.16 in. |
| b. Between conductor and sheath | 0.12 in. |
| 0000 conductors (diameter) | 0.46 in. |
| Impulse strength | 200 kv. |
| Geometric factor (Simmons) | 1.2 |
| Dielectric constant | 3.5 |

The surge impedance of the three conductors in the cable in parallel is:

$$Z_c = \frac{1.2}{0.0169 \times 3 \times \sqrt{3.5}} = 12.6$$

or 38.0 ohms per conductor.

The cable length in microseconds is:

$$2 \times \sqrt{3.5} = 3.75 \text{ microseconds}$$

Referring to Fig. 4 the maximum unprotected cable voltage as built up by wave reflections is given as 83 per cent of the traveling wave voltage on the line which was 1,500 kv. Therefore, the voltage in the cable would be 1,245 kv. Considering that the impulse strength of the cable is approximately 200 kv., protective equipment for the cable is necessary.

The first transmitted wave at the junction of the cable and line may be obtained from the formula:

$$E_2 = 2E_1 \frac{Z_2}{Z_1 + Z_2} = 212 \text{ kv.}$$

Since the cable strength is below this value of the first entering wave, an arrester is warranted at the junction of the cable and line. The first transmitted wave through the cable will approach double value at the "far" end of the cable when the "far" end is open circuited or connected to a transformer or other apparatus of high impedance. An arrester located at the junction of the overhead line and cable, limits the transmitted voltage, but the voltage appearing at the "far" end approaches double arrester voltage. This value should be compared with the strength of connected apparatus and also with cable and pothead strengths to determine the necessity for an arrester at that point.

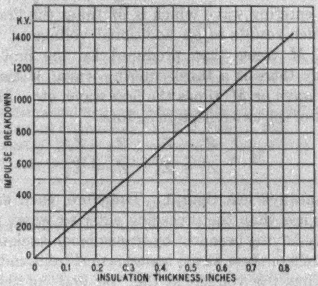

FIG. 7—APPROXIMATE WORKING VALUES OF IMPULSE BREAKDOWN OF CABLE INSULATION

From data on impregnated paper, solid and oil-filled single-conductor, and type h three-conductor cables

There may be cases where the cable strength and pothead flashover are somewhat greater than the first transmitted wave, and the point of weakest insulation is in the connected apparatus. In such cases, an arrester should be used to limit the voltage to a safe value for the apparatus, and located at the apparatus end of the cable. In this case additional protection would not seem warranted at the junction of the line and cable except for the case of direct stroke at or near that point.

There are so many ramifications to the problem of cable protection that it becomes very difficult to formulate general rules for their protection which will cover all cases.

However, it may be said that where low-voltage cables with corresponding low-impulse strength are connected to highly insulated lines such as a wooden pole structure having ungrounded hardware, safe practise requires the use of adequate arrester protection. Problems where the comparative strengths and lengths have other values may be examined to determine the degree of protection warranted for any particular installation in question.

## Appendix I

Assume a wave of vertical front and sloping tail represented by $E\epsilon^{-BT}$ and traveling on a line of surge impedance $Z_1$ into a cable of surge impedance $Z_2$ with a line of surge impedance $Z_3$ at the "far end." The front of the first wave entering the cable is: $\dfrac{2Z_2}{Z_1 + Z_2} E$.

This front is reflected at the "far end" of the cable, producing a total instantaneous voltage $AE$ where

$$A = \frac{2Z_2}{Z_1 + Z_2}\left[1 + \frac{Z_3 - Z_2}{Z_3 + Z_2}\right]$$

The reflected wave travels back to the "near end" of the cable where it is reflected again, thus producing a second entering wave which is $M$ times the first wave and which results in an additional voltage at the far end of $M$ times that produced by the first wave. Similarly there is a third entering wave, $M$ times the second wave or $M^2$ times the first wave, etc. $M$ is the product of the two reflection factors.

$$M = \frac{Z_1 - Z_2}{Z_1 + Z_2} \cdot \frac{Z_3 - Z_2}{Z_3 + Z_2}$$

and is always less than 1. Therefore, each entering wave is less than the preceding entering wave, part of the wave having been lost by transmission back into the line. Each of these waves has a vertical front and falling tail. Thus the voltage at the "far end" of the cable rises and then falls in a series of steps. At each step the voltage rises vertically and then falls until the next step. Therefore, the maximum voltage occurs at the beginning of one of these steps. If $T$ is the time required for a wave to travel twice the length of the cable, then at the beginning of the $n$th step the voltages of the preceding waves at the "far end" of the cable have been reduced by the factors $\epsilon^{-BT}$ $\epsilon^{-2Bt}$ etc. Therefore the total voltage at the $n$th step is:

$$E_{23}(n) = AE[M^{n-1} + M^{n-2}\,\epsilon^{-BT} + \ldots M^{n-n}\,\epsilon^{-(n-1)BT}]$$

This series is equal to the equivalent fractional expression:

$$E_{23}(n) = AE\,\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}}$$

The formula value for $n$ to give maximum value of $E_{23}$ is determined in the usual way:

$$\frac{d}{dn}(M^n - \epsilon^{-nBT}) = 0$$

$$n \text{ (for max } E_{23}) = \frac{\log \dfrac{-BT}{\log M}}{BT + \log M}$$

If this value of $n$ is not a whole number, then the two nearest whole numbers should be tried to determine which gives the maximum value. Usually, but not always, the nearest whole number gives the maximum value. The time at which the maximum value occurs is found by multiplying $T$ by the number of steps. In the above formula $\log M$ is negative since $M$ is always less than one.

The formula for $E_{12}$ at the near cable junction is derived in a similar way.

Let

$$F = \frac{Z_3 - Z_2}{Z_3 + Z_2} \text{ reflection factor at far terminal}$$

$$A^1 = \frac{2Z_2}{Z_1 + Z_2}$$

Then the initial voltage is $A^1E$.

The voltage at the second step is:

$$A^1E\epsilon^{-BT} + A^1E\,(M + F)$$

The voltage at the $n$th step is:

$$\begin{aligned} E_{12}(n) &= A^1E[\epsilon^{-(n-1)BT} + (M + F)\epsilon^{-(n-2)BT} \\ &\quad + M\,(M + F)\,\epsilon^{-(n-3)BT} + \ldots + M^{(n-2)}\,(M + F)] \\ &= A^1E[\epsilon^{-(n-1)BT} + (M + F)\,\epsilon^{-(n-2)BT}\,(1 + M\,\epsilon^{BT} \\ &\quad + M^2\,\epsilon^{2BT}\,\ldots + M^{n-2}\,\epsilon^{(n-2)BT})] \\ &= A^1E\left[\epsilon^{-(n-1)BT} + (M + \mathrm{F})\,\epsilon^{-(n-2)BT}\,\frac{1 - M^{(n-1)}\,\epsilon^{(n-1)BT}}{1 - M\,\epsilon^{BT}}\right] \\ &= A^1E\left[\frac{M^{n-1}\,(M + F) - \epsilon^{-nBT} - F\,\epsilon^{-(n-1)BT}}{M - \epsilon^{-BT}}\right] \end{aligned}$$

The value of $n$ for maximum $E_{12}$ is:

$$\frac{\log \dfrac{-BTM\,(1 + F\,\epsilon^{BT})}{(M + F)\log M}}{BT + \log M}$$

Fig. 6 shows how the value of $n$ varies with the cable length for case of a cable at the end of a line, the far end of the cable being open.

## Appendix II

The traveling wave energy passing a given point in the infinitesimal time $dt$ is:

$$EI\,dt = E\,dQ$$

$E$ = instantaneous voltage

$I$ = instantaneous current

The electrostatic energy that shifts from one side of this point to the other during time $dt$ and is associated with the infinitesimal length $ds$ is:

$$1/2\,C\,ds\,E^2 = 1/2\,E\,dQ \text{ since } Q = CE$$

Therefore, the electrostatic energy in a freely traveling wave is one-half the total energy and is equal to the electromagnetic energy.

$C$ = capacitance per unit length

$L$ = inductance per unit length

Then

$$1/2\, CE^2 = 1/2\, LI^2$$

$$E = I\sqrt{\frac{L}{C}} = IZ$$

where $Z$ = surge impedance

Since $ds = v\,dt$ where $v$ = velocity of propagation

$$EI\,dt = C\,ds\,E^2 = Cv\,dt\,E^2$$

$$v = \frac{I}{CE} = \frac{1}{CZ} = \frac{1}{\sqrt{LC}}$$

and $$Z = \frac{1}{CV}$$

If $L_0$ is inductance when the permeability is one and $C_0$ is the capacitance when the permittivity is one, then

$$V_0 = \frac{1}{\sqrt{L_0 C_0}} = \text{velocity of light}$$

In cables the permeability is one but the permittivity or dielectric constant has the value $K$.

$$V = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{KL_0 C_0}} = \frac{V_0}{\sqrt{K}}$$

Since $$Z = \frac{1}{CV}$$

$$Z = \frac{\sqrt{K}}{CV_0}$$

$V_0$ is approximately equal to 1,000 feet per microsecond (actually 984) and so if we let $C_1$ be the capacitance in microfarads per 1,000 ft. we have

$$Z = \frac{\sqrt{K}}{C_1} \text{ approximately}$$

This is a convenient formula for calculating the surge impedance of a cable.

In plotting curves involving traveling waves it is convenient to state the cable length in microseconds as the velocity varies in different cables. The actual length $S$ is equal to the length in microseconds $S_1$ times the velocity in feet per microsecond.

Therefore

$$S = S_1 \frac{1}{ZC_1}$$

$C$ = capacitance in $\mu$f. per 1,000 ft.

$S$ = length in 1,000 feet.

$$= \frac{S_1}{\sqrt{K}}$$

and $$S_1 = S\sqrt{K}$$

also $$S_1 = Z\,C_S$$

where

$C_S$ = capacitance of length $S$.

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6. *Cable Geometry and the Calculation of Current Carrying Capacity*, by D. M. Simmons, A.I.E.E. TRANS., Vol. 42, p. 600.

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10. "Underground Systems Reference Book," pp. 297, 298.

11. "Electrical Engineering," by E. J. Berg, p. 133.

12. *Traveling Waves on Transmission Systems*, by L. V. Bewley, TRANS. A.I.E.E., Vol. 50, p. 532.

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## Discussion

**Edward Beck:** The writer desires to register his accord with the observations of Messrs. Brinton, Buller, and Rudge about the improbability of low voltage cables connected to highly insulated lines such as those on wood poles being self-protecting; also those regarding the possibilities of high-voltage cables being self-protecting. As the authors remark, it may pay to examine specific installations for the degree of protection economically warranted. The writer has expressed such views in the reference cited in the bibliography and recently in the *Electric Journal*.

There is a phase of the behavior of traveling waves in cables which, so far as we are aware, has received little attention. The usual treatments of surges in cables consider the cable sheath grounded throughout its length. For this assumption the simple relations usually given are quite correct. It is not necessarily a fact, however, that in practise the cable sheath is grounded throughout its length. Often there may be a considerable ungrounded length of sheath between the entrance and the first sheath ground. It may even be the case that the sheath is entirely ungrounded or grounded through high resistance. The cable potentials in such cases are of practical importance. Some theoretical considerations led to the suspicion that a cable whose sheath is not grounded at the entrance may be subjected to high voltages internally.

The writer has made a series of tests on cables which shed some light on the subject. The cable set-up used was as shown in Fig. 1.

To lead up to the situation let us first consider a cable whose sheath is completely isolated from ground. Theoretically, such a cable should act very much like an open line with the same order of surge impedance and velocity of propagation since the presence of the ungrounded sheath has little effect on the distributed constants. It was found to be so by test. The measured surge impedance of the cable with ungrounded sheath was 492 ohms, and the velocity of propagation 890 feet per microsecond.

There should be no voltage across the cable insulation because the sheath will pick up by induction a voltage of the same order as the conductor voltage. The tests indicate that this is so, Fig. 2. At the far end the characteristic increase in voltage caused by reflection appears. There is still no potential difference between conductor and sheath. Such a cable needs no protection for itself, although apparatus connected to it does.

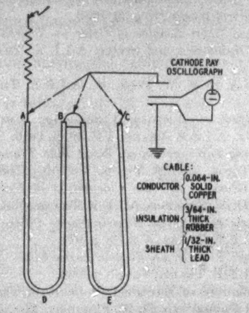
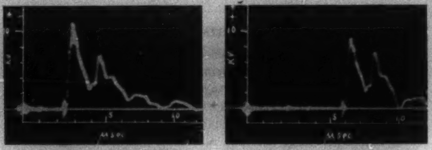

CATHODE RAY OSCILLOGRAPH
A
B
C
D
E
CABLE:
CONDUCTOR { 0.064-IN. SOLID COPPER
INSULATION { 3/64-IN. THICK RUBBER
SHEATH { 1/32-IN. THICK LEAD

FIG. 1—DIAGRAM OF CONNECTIONS FOR CABLE TESTS

*AB* = 352 ft: *BC* = 383 ft: *AD* = 233 ft: *BE* = 165 ft



Conductor voltage at *A*
Maximum = 10.7 kv

Sheath voltage at *A*
Maximum = 9 kv

Conductor voltage at *C*
Maximum = 17 kv

Sheath voltage at *C*
Maximum = 17.3 kv

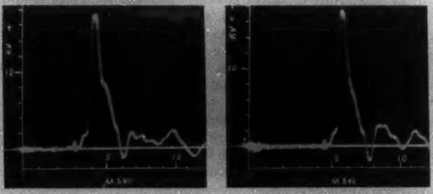
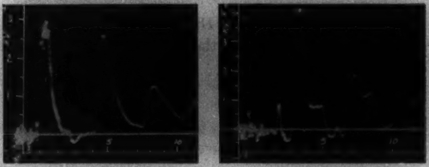


FIG. 2—VOLTAGES WITH CABLE SHEATH INSULATED FROM GROUND

Now consider the sheath grounded at the entrance only, Fig. 3. The characteristic reduction in conductor voltage takes place, the maximum voltage being 2.7 kv instead of 10.7 kv. The surge impedance of the cable is now much less, measurements indicated 39 ohms. The velocity of propagation is also less, 450 ft per microsecond. The cable now acts in the usually considered manner. The conductor potential appears between conductor and sheath. At the far end, *C*, the usual reflections occur, the sheath potential however, remains zero except for extraneous disturbances. Thus such a cable acts like the cables with grounded sheaths usually discussed. Measurements at *B*, the midpoint, indicated similar effects. A cable grounded at the entrance acts very like one grounded throughout its length and its insulation will be subjected to potential.

Now let us consider the cable with its sheath grounded only at the far end *C*, Fig. 4. While the surge is traveling from *A* to *C*, the cable acts as if the sheath were insulated, because the surge cannot tell that there is a ground at *C* until it reaches *C*. There is no reduction in entering voltage, therefore, until the reflection produced at *C* by the grounded sheath returns to *A*. The sheath potential at *A* again is the same as the conductor voltage, as far as is apparent, so again there is no voltage on the cable insulation at *A*. At *C* the sheath potential is zero because it is grounded, the voltage on the conductor is reduced below the incoming voltage measured at *A* because the cable turns from an ungrounded to a grounded one, in other words, the change from open line to cable takes place at *C*. Potential develops between the conductor and sheath at *C*. An arrester between conductor and sheath at *A* would do no good because it would not discharge since there is negligible potential difference between the conductor and sheath at *A*. This is important because it may easily appear offhand that an arrester between conductor and sheath would protect the cable regardless of grounding conditions. In the protection of distribution transformers, for instance, it is a fact that if the transformer insulation is shunted by arresters, it is protected regardless of grounds. This does not hold for cables. The point of greatest danger to the cable is where the sheath ground is, or at the far end if the conductor terminates there.



Conductor voltage at *A*
Maximum = 2.7 kv

Conductor voltage at *C*
Maximum = 4.2 kv

Sheath voltage at *C*

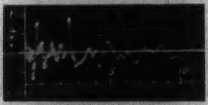


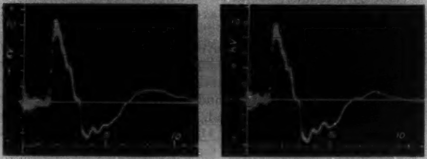
FIG. 3—VOLTAGES WITH CABLE SHEATH GROUNDED AT ENTRANCE, POINT *A*

Tests with the cable sheath grounded at *B*, the midpoint, gave similar results at the entrance *A*. Potential across the cable insulation occurred at the midpoint where the ground was located. At the far end *C* some potential also developed by reflection phenomena. Arresters between the conductor and sheath at *A* had no effect. Arresters at *C* changed the measured voltages.

Many oscillograms were made during these tests under many conditions of grounding and protection. The conclusions are:

A cable with ungrounded sheath acts the same as an over head line. No potential will develop between the conductor and the cable sheath and such a cable requires no protection for itself. The traveling wave voltages in such a cable will act as though the cable were an overhead line. Thus short pieces of cable interposed in overhead lines, if the sheath is insulated will require no protection. If, however, the sheath should be grounded purposely or accidentally, the cable will require protection because high potentials will then develop between the conductor and the sheath.

The connection of a lightning arrester between the conductor and the sheath at the cable entrance with no ground is not to be recommended in general. If the cable sheath is not grounded for some distance from the entrance, potential differences between the conductor and sheath may not develop at the entrance and the maximum potential difference will probably develop where the sheath is grounded. The arrester between conductor and cable sheath at the entrance may not discharge and therefore will not exert any protective effect on the cable. It will be best to have a definite ground at the cable entrance.



Conductor voltage at *A*
Maximum = 10.5 kv

Sheath voltage at *A*
Maximum = 9.5 kv

Conductor voltage at *C*

FIG. 4—VOLTAGES WITH CABLE SHEATH GROUNDED AT FAR END, POINT *C*, ONLY

**L. V. Bewley:** This paper, treating of the theory and calculations of traveling wave voltages in cables, in conjunction with an earlier paper[2] dealing with the experimental work, forms a very complete treatment of the problem. It appears, however, that the generality of the paper can be increased without undue space requirements. With that end in view the following suggestions are submitted.

1. On the first page, under *b*, it should be explicitly stated that both the *self-* and *mutual-*surge impedances are to be taken into consideration. For example, suppose that a three-phase overhead line enters three separate single-phase cables. Now if lightning strikes all three lines, the equivalent surge impedance of the overhead line is approximately

$$Z_1 = \frac{Z + 2Z'}{3} = \frac{500 + 2 \times 100}{3} = 214$$

where $Z = 500$ is the average self-surge impedance per conductor and $Z' = 100$ is the average mutual-surge impedance between pairs of conductors. Then if the self-surge impedance of each cable is 60 ohms

$$Z_2 = \frac{60}{3} = 20$$

is the equivalent surge impedance of the three cables in parallel, and the refraction factor at the line—cable junction is

$$\frac{2Z_2}{Z_1 + Z_2} = \frac{40}{234} = 0.171$$

Had the mutual-surge impedance been ignored the refraction factor would have calculated

$$\frac{2Z_2}{Z_1 + Z_2} = \frac{2 \times 60}{500 + 60} = 0.214$$

which is 25 per cent higher than the correct value.

2. The authors speak of having neglected attenuation. On the assumption of a true exponential attenuation, the formula in their Appendix I becomes

$$E_{23(n)} = AE\left[\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}}\right]\epsilon^{-\alpha T}$$

where $\alpha$ is the attenuation factor. This is easily verified.

3. The effect of waves with rounded fronts and exponential tails, such as can be represented by

$$E\,(\epsilon^{-BT} - \epsilon^{-bt})$$

follows at once, by the principle of superposition, as

$$E_{23(n)} = AE\left\{\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}} - \frac{M^n - \epsilon^{-nbT}}{M - \epsilon^{-bT}}\right\}\epsilon^{-\alpha T}$$

Since the effect of the front is small the maximum will occur at practically the same time as for the wave with an abrupt front ($b = \infty$), that is at substantially the same value of $n$ as given by the authors.

4. In these formulas, $A$ and $M$ may be put in the form

$$A = \frac{2\,(Z_2/Z_1)}{1 + (Z_2/Z_1)} \cdot \frac{2\,(Z_3/Z_2)}{1 + (Z_3/Z_2)}$$

$$M = \frac{1 - (Z_2/Z_1)}{1 + (Z_2/Z_1)} \cdot \frac{(Z_3/Z_2) - 1}{(Z_3/Z_2) + 1}$$

from which it is seen that it is the *relative* and not the *absolute* values of $Z_1$, $Z_2$ and $Z_3$ which control the transient. For example, the transient would be identical for any of the following corresponding values.

$Z_3 = 300 - 400 - 534$
$Z_2 = 267 - 300 - 400$
$Z_1 = 67 - 75 - 100$

Hereby the curves in the authors' Figs. 3 and 4 could be condensed into a single figure containing really more information, and their Fig. 5 could likewise be made more general.

**J. E. Clem:** About a year and a half ago I had occasion to analyze the voltages set up in a cable at the end of a transmission line by the impact of a traveling wave. The report made at that time, with a few modifications, is given as a discussion of the present paper.

When a traveling wave of any kind arrives at the junction between an overhead line and a cable, the voltage is initially reduced because of the lower surge impedance of the cable. With a rectangular wave, if it is long enough or the cable short enough, the voltage in the cable will build up to twice the voltage of the incident wave when the exit end of the cable is open-circuited, or to the voltage of the incident wave when the exit end of the cable connects to an overhead line. Usually the length of the traveling wave is such that these maximum voltages are not reached.

The usual traveling waves encountered in practise have a front with an approximate logarithmic increase and a tail with an approximate logarithmic decrease. The length of the front and the length of the tail may be of any value. This analysis was made to determine the maximum voltage to be expected with a damped incident wave. One of the waves proposed for insulation coordination is what is known as the 1.5–40 microsecond wave and calculations were made using this wave with, however, a slight modification (the use of a rectangular front, 0–40 microsecond, wave) which has no appreciable effect on the results of the calculations.

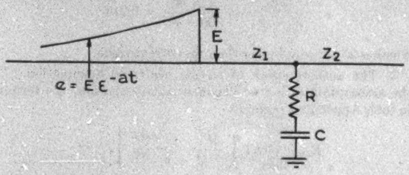


FIG. 5—EQUIVALENT CIRCUIT TO REPRESENT A CABLE

A cable has distributed constants and for a traveling wave has appreciable series resistance and shunt conductance. On this account it is important to know whether or not calculations made on the basis of lumped constants will give results of engineering accuracy. Accordingly, two calculations were made. In the first the cable was assumed to be represented by a resistance and capacitance in series. For this calculation the total capacitance of the cable was used and the resistance was estimated on the basis of a 1.5 per cent power factor in the cable. For the calculation with distributed constants a specific cable was taken. Due to the great amount of labor required for the calculations with distributed constants it was thought that but one calculation would be sufficient.

The equations for the calculations with the lumped capacitance are developed from Fig. 5 as follows: In this figure

$E$ = initial voltage of a traveling wave
$Z_1$ = surge impedance of line on entrance side of cable
$Z_2$ = surge impedance of line at exit side of cable
$R$ = effective resistance of cable estimated from power factor
$C$ = total capacitance of cable

Since a damped wave instead of a rectangular wave is being considered, it is necessary to represent the incident wave by the following equation.

$$e = E\,\epsilon^{-at} \tag{1}$$

The operational equations for the voltage $e_0$ across the receiving circuit can be shown to be

$$e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,\frac{R}{R_0}\,\frac{p+\dfrac{1}{RC}}{p+\dfrac{1}{R_0C}}\,\epsilon^{-at}\,1 \tag{2}$$

The solution of this equation is given by the usual process and is

$$e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,\frac{1-RCa}{1-R_0Ca}\left\{\epsilon^{-at} - \frac{R_0-R}{(1-RCa)\,R_0}\,\epsilon^{-\frac{t}{R_0C}}\right\} \tag{3}$$

In order to find the maximum voltage this equation is differentiated and the differential placed equal to zero. The maximum voltage is found to be

$$\text{Max. } e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,(1-RCa)\,M^{\frac{R_0Ca}{1-R_0Ca}} \tag{4}$$

which occurs at the time $T$ given by

$$T = -\frac{1}{a}\log M^{\frac{R_0Ca}{1-R_0Ca}} \tag{5}$$

In these equations $R_0$ and $M$ are defined as follows:

$$M = \left(1+\frac{R}{Z_1}\,\frac{Z_1+Z_2}{Z_2}\right)(1-RCa)\,R_0Ca \tag{6a}$$

$$R_0 = R + Z_1\,\frac{Z_2}{Z_1+Z_2} \tag{6b}$$

In Fig. 7 are shown two curves calculated from these equations showing the maximum voltage produced on varying lengths of cable by a 40-microsecond wave, with the cable first assumed as open at the exit end and then as connected to another overhead line.

Field tests have been made covering these two cases, the cable used having a capacitance of about 0.037 microfarads. For this value the curves give a maximum voltage on the cable for the open end condition of 1.17$E$, and 0.68$E$ when the cable joins an overhead line at the exit end. In the test referred to these ratios were found to be about 1.20 and 0.74 respectively. Although the wave used in the tests was not exactly the same as that used in the calculations it appears that not much difference in the results was found from tests with different waves.

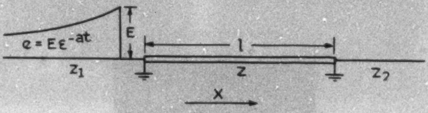


FIG. 6

The calculations for the case when the distributed constants of a cable are taken into account were made from equations developed as follows: Refer to Fig. 6 which shows a cable of length $l$ between two transmission lines. Following is an additional list of symbols.

$Z$ = surge impedance of cable
$L$ = inductance of cable per unit length
$r$ = resistance of cable per unit length
$C$ = capacitance of cable per unit length
$g$ = leakance of cable per unit length
$v$ = velocity of the impulse in the cable
$l$ = length of cable

If these cable characteristics are associated as follows:

$$\rho = \frac{r}{2L} + \frac{g}{2C} \tag{7a}$$

$$\sigma = \frac{r}{2L} + \frac{g}{2C} \tag{7b}$$

$$v = \frac{1}{\sqrt{LC}} \tag{8}$$

$$K = \frac{2Z}{Z+Z_1} \tag{9}$$

The voltage $e_c$ at any point $x$ in the cable can be shown to be

$$e_c = KE\epsilon^{-\frac{x}{v}\sqrt{(p+\rho)^2-\sigma^2}}\,\epsilon^{-at}\,1 \tag{10}$$

The solution of this equation is

$$e_c = KE\epsilon^{-\rho t}\left\{\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)} + \frac{x}{v}\,\frac{\sigma^2}{2}\,\frac{1}{(\rho-a)}\left(\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)}-1\right)\right.$$
$$+\frac{x^2}{v^2}\,\frac{\sigma^2}{2}\,\frac{1}{\underline{/2}}\,\frac{1}{(\rho-a)^2}\Bigg[\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)}$$
$$\left.-1-(\rho-a)\left(t-\frac{x}{v}\right)\Bigg]+\ldots\right\}1_{\frac{x}{v}} \tag{11}$$

The operational equation shown in equation (10) is the conventional one except that the applied voltage is

$$e = E\epsilon^{-at} \tag{1}$$

instead of the conventional rectangular wave and the fact that $K$ has been introduced to include the reflection occurring at the entrance end of the cable. The solution (11) of this equation is entirely new and is given in an entirely different form from that usually shown when the conventional solution for the rectangular wave is given. The solutions usually given involve more labor for the calculations and the fact that they apply to the entrance end of the cable is not at all obvious and further they are suitable only for rectangular waves. The solution here given applies to any shape of the wave, permits calculations of greater accuracy with less labor and obviously holds for the entrance end of the cable.

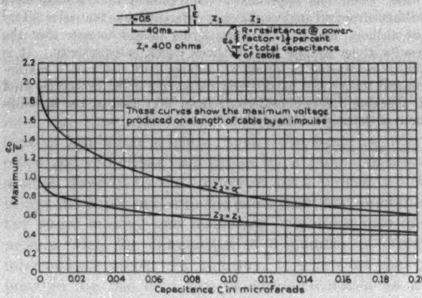


FIG. 7

Inasmuch as the voltage produced in the cable by the wave depends upon reflections of the traveling wave, certain approximations were made and the equations modified to permit calculations for either end of the cable to determine the voltage produced by any number of reflections. The approximations made do not appreciably affect the accuracy over the time period of lightning surges, and the final equations are:

$$e_1 = KE\,\epsilon^{-a2n\frac{l}{v}} \left\{ 1 + \frac{K_1}{K_3} \frac{K_3 K_4 \epsilon^{-(\rho-a)2\frac{l}{v}} \left(1 + K_3^n K_4^n \epsilon^{-(\rho-a)2n\frac{l}{v}}\right)}{1 - K_3 K_4 \epsilon^{-(\rho-a)2\frac{l}{v}}} \right\} \tag{12}$$

$$e_2 = KE\frac{K_2}{K_3 K_4}\epsilon^{-(2n-1)a\frac{l}{v}} \frac{K_3 K_4 \epsilon^{-(\rho-a)\frac{l}{v}} \left(1 - K_3^n K_4^n \epsilon^{-(\rho-a)2n\frac{l}{v}}\right)}{1 - K_3 K_4 \epsilon^{-(\rho-a)2n\frac{l}{v}}}$$

In these equations

$$K_1 = \frac{2Z_1}{Z + Z_1} \qquad K_3 = \frac{Z_1 - Z}{Z_1 + Z}$$
$$K_2 = \frac{2Z_2}{Z + Z_1} \qquad K_4 = \frac{Z_2 - Z}{Z_2 + Z} \tag{13}$$

In Fig. 8 are given curves showing how the voltage builds up in a 1,000-ft length of cable when a 40-microsecond wave comes in from an overhead line. These calculations are based on the assumptions that the wave comes in over one conductor and in this case the inductance and capacitance involved should be from one conductor to sheath. The determination of these two factors involved a little manipulation. Published data on cable capacitance usually give two values, but it was found that these two values were not consistent with the correct geometric proportions of the cable. That is, if these two capacitances were separately calculated from the geometric proportions of the cable, a different permittivity factor would have to be used in each case. On this account calculations were remade using permittivity factor of 4. The capacitance was calculated between one conductor and sheath and the corresponding inductance determined from this quantity through the velocity relationship between inductance and capacitance. The series resistance was taken ~~as three times~~ the conductor resistance to allow for sheath losses and the conductance was estimated on the basis of a power factor of 10 per cent to allow for insulation losses.

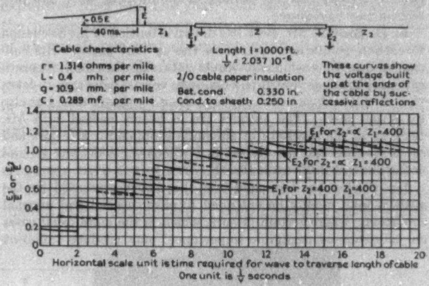


FIG. 8

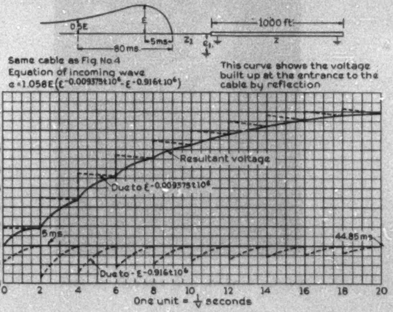


FIG. 9

As a further check, calculations were made with an applied wave closely approximating the wave used in the tests. The results are shown in Fig. 9. The maximum calculated voltage is higher than the tested maximum indicating that the more precise calculations probably indicate too high a voltage. This is no doubt due to greater losses in the cable or impulse than were assumed for the calculations.

The comparison of these calculations with previous calculations and with the test results indicates that the need of cable protection can be determined by calculations made on the basis of lumped capacitance.

If the insulation of the cable is properly coordinated with the line to which it is connected, then no protection would be needed for the cable when the voltage produced by the traveling wave in the cable is equal to or less than the voltage of the arriving wave. On this basis it appears from calculations that cable lengths from 500 to 4,000 ft might need protection, depending upon the specific conditions in each case. Longer cables very probably do not need protection. It is recommended therefore that any cable installation less than 4,000 ft in length be checked to find out whether or not protection is needed. If, on the basis that the cable at the exit end is connected to a transformer or to a very high surge impedance, the voltage appearing on the cable is greater than the voltage of the incident wave and protection may be required.

**F. H. Buller:** Mr. Beck has drawn attention in his discussion to certain points not covered in the present paper. His conclusions are those which one would naturally draw from theoretical considerations; but it is, of course, very satisfactory to learn that these conclusions are supported not by theory only but also by actual tests. The authors are in hearty accord with Mr. Beck as to the necessity of adequate grounds for arresters and cable sheaths, and the desirability of locating a definite ground at the line end of the cable sheath.

Mr. Bewley has indicated how the theory presented by the authors may readily be extended to cover special and unusual conditions, where certain factors, which in the more usual cases are of minor or negligible importance, may produce sufficient effect to affect considerably the accuracy of any calculation in which they are neglected. The four points covered in Mr. Bewley's discussion are answered in the following:

1. The authors felt that this was rather obvious and therefore did not discuss it as fully as might otherwise have been done. However, it is appreciated that this point is one which might be overlooked; and it is well, therefore, that attention has been drawn to it.

2. It has been already pointed out that in the case of short cables, which are the ones that usually need protection, the attenuation is negligible. The formula given by Mr. Bewley, however, is, of course, of value in those cases where it is desirable or necessary to take attenuation into account.

3. The authors are glad to observe that Mr. Bewley agrees with them that the effect of wave front is very slight for the types of wave under consideration. In the study of waves of a different character, however, Mr. Bewley's formula might well prove to be very useful.

4. The authors have already found that Mr. Bewley's suggestion is an extremely useful one in those cases where a large number of practical calculations must be made.

Mr. Clem has approached the problem of traveling wave voltages from an angle somewhat different from that selected by the authors; and it is very gratifying indeed to note that the results given by the two methods check satisfactorily. It is always reassuring to obtain an independent check on a mathematical theory and particularly reassuring if the procedure used in checking differs considerably from that used in the development of the original theory.

# Pulp Insulation for Telephone Cables

BY H. G. WALKER* and L. S. FORD†
Non-member — Associate, A.I.E.E.

*Synopsis.—A new type of insulation has been developed by the Bell System engineers and put into use for exchange area cables. This insulation consists of a continuous pulp or paper sleeve formed directly on the conductor by a modified paper making process. The manufacture and use of pulp-insulated wire cables involves unique changes in manufacturing equipment, materials and methods, in cable design and installation practises. The development has covered a period of some ten years and is the result of combined manufacturing, engineering, and field studies.*

* * * * *

## INTRODUCTION

OPEN wires were almost universally used for the transmission of speech in the days when telephony was young but gradually, as the need arose, the art of cable making was evolved. Today, except in the rural districts, the open wire lines have been almost entirely replaced by aerial or underground cable. The conductors in the early metal covered cables were insulated with one or two servings of cotton but in the late eighties Bell System engineers developed a spirally wrapped paper insulation so much better electrically and lower in cost that it was shortly adopted as the standard insulation for telephone cables by the growing industry. Now after some forty years of service this type of insulation is being rapidly displaced for inter-office and subscriber loop cables by a pulp insulation applied directly to the conductor by a process which brings the paper mill into the cable plant and combines the paper making and insulating operations into one process with the elimination of a number of costly intermediate steps. In addition, this process makes possible the use of a less expensive material as an insulating medium.

In order to establish a background for the logical consideration of the pulp insulation development it is desirable to cover briefly the materials, equipment and methods that have gradually been developed for the rapid application and economic use of paper ribbon insulation and indicate the limitations involved.

For many years the standard paper in this country for insulating conductors for lead-sheathed telephone cables was made from a stock composed of all old rope or old rope and a small admixture of cotton, the fibers of the rope being chiefly manila from the plant *Musa Textilis* or hemp from the plant *Cannabis Sativa*. Papers of such composition, slit into long narrow strips, were applied helically around the wire to form the insulated conductor. Experience had proved them to be highly suitable as an insulating medium, both as to structural permanency and electrical characteristics and to be sufficiently flexible and strong mechanically to admit of ready application to the conductor in manufacture and to withstand subsequent handling in service. With the increasing demand for insulating papers, however, came the urge for the finding of a suitable less expensive fiber and the year 1920 saw the adoption, for the larger sizes of paper only, of a formula composed of about 40 per cent chemical wood pulp and the remainder rope stock. This wood fiber is of the spruce or other coniferous tree species prepared by the sulfate or "Kraft" process. It is required to have a high cellulose content and to be as free from water soluble salts as the best manufacturing practise will permit. Extensive tests have demonstrated that it compares favorably in stability and permanence with the well-established manila fiber. In the case of pulp insulated cable which is discussed in this paper the raw material used is 100 per cent of this wood fiber.

FIG. 1—RIBBON PAPER INSULATORS

The present day ribbon paper insulating machine as developed by the Western Electric Company is essentially a rotatable hollow tapered spindle centrally mounted on and integral with a light weight disk about 15 inches in diameter. (Fig. 1.) The wire to be insulated passes through the spindle over a capstan and to the take-up spool. The insulating paper wound into a pad or disk is slipped over the spindle and supported by the metal disk. This whole assembly is arranged to rotate rapidly around the wire and feed the paper ribbon from the periphery of the pad through guides so as to form a continuous spiral wrapping around the wire which is advanced at a definite speed by the capstan. The speed of rotation of the spindle is approximately 3,300 r.p.m. and the wire advances from 175 to 200 feet per minute depending on the length of wrap.

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†Bell Telephone Laboratories, Inc.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

From a process standpoint manila paper was selected originally because of its strength and elasticity, and in the development of equipment to serve it, full advantage was taken of these two characteristics, particularly for the insulation of the finer gages of wire. This fact tended to handicap the adaptation of cheaper papers to this purpose when the changing conditions in the paper industry made such a step desirable, since the readily available substitutes were somewhat inferior in these two respects. Studies were undertaken to modify the equipment for serving ribbon paper with the idea of adapting it for handling this paper, but with only indifferent success. The mixing of varying amounts of wood pulp with manila stock proved to be a successful solution in the case of heavier papers, but in the thinner ones the results were not satisfactory, and progress in this direction was at a standstill.

## THE DEVELOPMENT OF PULP INSULATED WIRE

In line with the generally recognized need for a radical change in the insulation situation, some work was initiated in 1921 with the idea of determining the possibilities of producing a continuous homogeneous paper covering directly on the wire, and a scheme was worked out, which after some preliminary experiments, gave sufficient promise of success to suggest the desirability of going ahead with the development of the idea and the mechanism to carry it out.

A crude paper machine of the cylinder type was built and with this the feasibility of the basic idea was demonstrated. Dryers were next improvised and sufficient wire was insulated to give a few short test cables. These, of course, were made from carefully selected insulation for only a small part of the wire made was usable. The test results on these cables were sufficiently interesting to warrant proceeding further with the project. After considerable study and experiment it was decided to build a ten-wire machine adaptable to future expansion if the anticipated results were realized. This 10-wire machine was started up with very indifferent success in January, 1924. During that year an operating technique was gradually developed and numerous improvements made in the equipment. In 1925, a great many test cables were made and several were installed for use in the telephone plant. Experience with the 10-wire operation and product finally became so satisfactory that it was decided to expand the machine to a 50-wire capacity and put it on as near a commercial basis as possible, in order that its operation, product, and economics might be studied to better advantage. Accordingly, the necessary auxiliary equipment was purchased and installed and the machine converted to a 50-wire basis.

The installation was completed early in 1928 and the machine put in experimental operation about March of that year. As rapidly as possible crews were broken in and late that summer the machine was placed on a regular operating basis with three complete crews on a twenty-four hour day and six-day week. It continued to operate on this basis until 1931, when ten more wires were added. This product was cabled into 26 and 24 A.W.G. cables on standard cabling equipment with no major difficulties and installed in commercial telephone plant by the operating companies. No serious operating trouble has developed in any of this cable.

The pulp insulated wire capacity now at the Hawthorne and Kearny plant is approximately 225 million conductor feet per week and all 24 and 26 A.W.G. exchange area cables are being manufactured from pulp insulated wire.

## PROCESS

Essentially the process consists in forming simultaneously on a modified cylinder paper machine 60 narrow continuous sheets of paper with a single strand of wire enclosed in each sheet, pressing the excess moisture from the sheets, turning them down so as to form a uniform cylindrical coating of wet pulp around the wire and then driving the water from this coating by drying at a high temperature. (Fig. 2.)

FIG. 2—GENERAL VIEW OF PULP INSULATING EQUIPMENT

Take-up and dryer in left foreground, polishers and wet machine in right center. Wire supply and pulp preparation equipment in right background

The insulating material is given practically the same treatment in a beater as it would receive in paper making, but without the addition of sizing or loading. The beaten pulp is stored in a large tank from which it is pumped to a mix box for dilution with water before passing to the screen where coarse particles and lumps are removed. (Fig. 3.)

For the next operation a modified paper machine of the cylinder type is used. The mixture of pulp and water is fed into the cylinder vat by gravity from the screen. The cylinder mold itself is divided into 60 narrow, uniform sections by dams or deckles on the surface of the wire cloth covering. The bare conductors coming to the machine are guided so that one conductor passes around the mold in each of the sections. As the mold is rotated in the water suspension of pulp in the vat, a narrow continuous sheet of paper with a conductor embedded in it is formed in each section by the simple paper making process of straining the fibers from the suspension as the water flows through the fine wire cloth covering the mold, under the slight head maintained outside the mold. These sheets are transferred from the mold to a woolen felt by the pressure of a couch roll and carried by it through two presses which take out a considerable part of the water and leave the material in shape to be turned down to the final form. This is done by passing the conductors embedded in the narrow sheets through individual polishers which turn the wet sheet down into a uniform covering of a size determined to a large extent by the amount of pulp deposited in the sheet. These polishers are simply rapidly rotating heads carrying three specially shaped blades so arranged that one blade deflects the traveling wire and sheet from a straight line against the other two with a pressure controlled by the tension on the wire.

Fig. 3—Wire Supply and Pulp Preparation Equipment

The wet cylindrical insulation is then dried to about a 9 per cent moisture content by a single passage through a horizontal electric furnace 26 feet long the wet end of which is maintained at a temperature of about 1,500 deg. fahr. and the dry or tempering end at something under 800 deg. fahr. The wires are carried through the drier by a rotary pulling mechanism designed to minimize the crushing or flattening of the dried insulation. This device delivers the finished product to the take-ups for spooling. The machine is operated at about 130 feet per minute.

Considerable amounts of water are used in the process, for in this, as in all paper making processes, water acts not only as a carrier for the fibers, but it forms some sort of a loose chemical or mechanical combination with them in the beater which is one of the principal factors in determining the final characteristics of the material. The approximate fiber concentrations at the various steps of manufacture are as follows:

| | Per cent |
|---|---|
| Beater | 3.5-4 |
| Storage | 1.3 |
| Screen | 0.07 |
| Cylinder vat | 0.05 |
| Polishers | 28 |
| Completed insulation | 91 |
| Finished cable | 100 |

### Some Problems Involved

In theory the whole process is remarkably simple, but from the practical standpoint, many intricate problems had to be solved before satisfactory operation was possible. In some cases it was rather difficult to segregate the problems for study as there were so many variables involved. Gradually, however, these details have been cleared up and today operation is quite satisfactory. A brief survey of some of the more important problems and their solutions may be of interest.

*Continuous Operation.* It is quite essential, from an economic standpoint, that the machine should operate continuously. The fact that the supply spools carry only a limited amount of wire necessitated the working out of a dependable means for shifting from an empty to a full spool without a shutdown or break in conductor or insulation. This is accomplished by taking the wire off over the head of a spool by means of a flyer and brazing the inner end of the wire on one spool to the outer end of the next, Fig. 4. Again in spooling the finished material at the dry end, the wire must be transferred from a full spool to an empty spool without interfering with the operation of the machine, Fig. 5. This has been taken care of very simply by providing two spool positions for each wire with a simple manual means of shifting from one to the other.

Fig. 4—Changing Spools at Supply End

*Broken Wires.* In spite of all the care that can be exercised, wires break at times and as a matter of economy, methods of restringing the broken wires with the machine in operation had to be worked out as shown in Fig. 6. Continuous six-day week operation is now possible without shutdowns except for the midweek clean-up.

Fig. 5—Changing Spools at Take-Up

*Wire Cleaning.* The supply wire comes to the machine on spools. It is spooled on the wire drawing machine and annealed on the spool. The surface of this wire, annealed with the drawing compound on it, seems to act somewhat as a repellant to wet pulp and causes a ragged, broken insulation. This is probably due to a surface tension effect. This action caused considerable trouble in the early stages of the work as the blame was placed on polishers, pulp, felts, or anything but the wire surface. Finally it became apparent that the surface condition of the wire was a large factor and the trouble was eliminated by passing all the bare wires through an a-c. electrolytic cleaner between the supply stand and the wet machine.

Fig. 6—Stringing in a Wire at Polishers

*Tensions.* Fine gage copper wire is soft and easily stretched, pulp insulation in the wet form possesses very little strength, and in the dry form its elongation is much lower than spirally wrapped ribbon insulation, hence it is necessary at every step in the process to maintain minimum tensions in order that the wire may not be stretched and the insulation opened. Devices have been developed that are quite efficient in holding tensions within the safe range.

*Pick-Up.* In the early operating stages the pick-up from the mold was at times ragged and uneven and the sheet formation not all that could be desired. It was found that these conditions could be materially improved by the addition of a very small amount of soap to the pulp suspension immediately before it reaches the machine.

*Polishing.* In connection with the operation of polishing the sheet down to a circular insulation, it has been found that a water content of approximately 72 per cent is preferable to a dryer or wetter sheet as it seems to felt down and form a more homogeneous insulation. The polisher itself has required a considerable amount of development work to insure a continuous uniform product and avoid stripping when a lump or break in the sheet occurs.

*Drying.* Several methods of drying pulp insulation were given a thorough trial but a completely satisfactory drier did not prove a simple thing to find. Finally, however, it was discovered that very rapid drying caused less shrinkage than slower drying, and so resulted in a less dense insulation. As a low density insulation is very desirable electrically, this was the deciding factor in adopting high temperature radiant heat drying and experience has amply justified the decision.

*Operation.* The development of operating technique and methods offered some difficulties as the process is neither wholly paper making nor wire handling. Preliminary methods were worked out by engineers on the machine. Then regular operators were recruited for the most part from the operating organization and broken in to the work. Most of them had never seen a paper machine before but they became very efficient in a surprisingly short time and there have been no prejudices acquired on regular paper machines to overcome.

*Making Narrow Ribbons.* The making of narrow uniform ribbons has given considerable trouble. The most satisfactory solution of this problem to date is the use of deckles or dams painted on the mold mechanically at spaced intervals. Apparently very good life can be expected from such a mold.

*Defective Wire.* It is necessary to mark defects in the completed wire by placing a white tag in the winding in order that repairs may be made by the twister operators, as there is no opportunity to make them at the pulp machine take-ups. Short breaks in the insulation were often passed unnoticed by the operators so a bare wire detector was put in which sounds an alarm, indicates the spool position by a light and records the break by number on a position counter and on a master counter. If any one spool shows excessive defects it is rejected.

## GENERAL PHYSICAL CHARACTERISTICS

Pulp insulation is a new product and has certain inherent characteristics. These characteristics may be modified somewhat by choice of materials and methods of manufacture but they can not be entirely controlled. A brief survey of these characteristics may be of interest to illustrate the possibilities and limitations of the product. This survey covers only 24 and 26 A.W.G. wire as these are the sizes which have been run almost exclusively to date. It should be noted, however, that wires ranging in size from 19 to 28 A.W.G. have been covered successfully.

Some of the physical characteristics of the insulation are shown below in tabular form giving the possible range of values obtainable. They are controlled by the beating of the pulp, the amount of pulp fed to the machine, the dryness of the sheet in the polishers, and the speed of drying.

| | |
|---|---|
| Diameter of insulated wire—inches........ | 0.030 to 0.050 for 24 A.W.G.<br>0.026 to 0.040 for 26 A.W.G. |
| Weight of dry pulp—grams per foot....... | 0.045 to 0.12 for 24 A.W.G.<br>0.040 to 0.095 for 26 A.W.G. |
| Density—ratio of fiber to total volume.... | 35% to 55%—independent of gage |

The tensile strength and flexibility of the insulation can be varied through rather wide limits by different treatments during manufacture. The elongation is quite comparable to that of ordinary paper and is not susceptible of much variation. The insulation is made sufficiently strong and flexible to withstand the various operations incident to cable fabrication and subsequent handling yet not so tough that it cannot be readily removed from the wire at the point of splicing.

The surface of the insulation has a rather rough blotting paper appearance, though some variation is possible by changes in the beating. The cross-section is circular with the conductor in the center in the ideal case, but because of limitations imposed by practical operating considerations there is a tendency toward some eccentricity and flattening of the insulation.

## PULP INSULATED CABLES

*Design.* The smallest wires now used in commercial telephone cables are 24 and 26 A.W.G. and it has been found that pulp is particularly suitable for insulating such fine wires. Here it is in direct competition with non-wood content strip paper that has been giving satisfactory quality performance. To displace the old standard, pulp must meet this competition and give a greater return for the money invested.

Telephone cable circuits are normally subjected to only a low dielectric stress which permits their being placed in close proximity to one another and the primary requirement of the insulation is that it be distributed in a thin layer of uniform application, with the wire well centered so that each conductor when packed into a cable is completely insulated from its neighbors throughout its length. The mean radial thickness of the pulp insulation for the 26 A.W.G. wire which is in common use is less than 0.01 inch and for 24 A.W.G. which is the next larger size of wire usually used for telephone cables this value is about 0.011 inch. The pulp is prepared and applied to the conductor in such a manner that the fibers pack together to form a cover with sufficient strength and elasticity to withstand the handling the insulated wire must receive and yet be as light as possible in weight per unit volume in order to obtain the best electrical characteristics.

At the time this development was started 24 A.W.G. wire was the finest regularly used and the earlier pulp cables were confined to this gage. Pulp insulated wire is structurally more like textile insulated wire than air-spaced paper ribbon insulated wire. The insulation is firm with no appreciable air gap between it and the wire, and bundles of wires nestle together differently when grouped into a given space. Furthermore, it was found that when pairs of conductors were stranded together in the usual manner of concentric layers each reversed in direction, the unit thus formed was considerably less flexible than the standard construction. This is apparently caused by the greater frictional resistance between layers sliding over each other as the cable is bent, thus causing sharp kinks for even moderate bends. While this feature is less pronounced for small cables, it is, of course, objectionable and an improvement in the handling qualities is effected by stranding several layers in the same direction rather than employing the single reverse layer construction.

For the large size cable, a design whereby the pairs are first grouped into units of fifty-one or one hundred and one, all the pairs in these units being stranded in the same direction and the units then stranded together into a cable, gives a construction which seems to offer the most satisfactory arrangement. Thus, for example, a 1,212-pair cable is made up of 12 units of 101 pairs each, arranged with four units in the center and eight in a surrounding layer, and an 1,818-pair cable is laid up with two units in the center surrounded by six units in the first layer and ten units in the second layer. Fig. 7 shows a short section of 1,818-pair 26 A.W.G. cable with the units separated. One might expect these rather large units would not group themselves together into a circular shape without poor utilization of the space they occupy but it has been found that by properly constructing the individual units and by suitable arrangement of the cable layup, a cross-section is obtained with the groups keystoning together nicely and presenting no noticeable voids.

The cable core must also have a certain firmness or density to give the best support to the sheath and insure satisfactory handling as the cables are being installed. With ribbon paper insulation the ratio of the amount of insulation to the non-copper space in a cable was found to be a fairly good criterion of the firmness required. With the fundamentally different physical characteristics of the pulp insulated wire this relationship was altered and experimental trials were therefore necessary to determine the approximate size of pulp insulated wire most suitable for the space it was to occupy in cable form. There is some latitude here in the distribution of a given amount of fiber but taking into account both the mechanical and electrical requirements, the diameter for the insulated conductor finally selected as the most satisfactory for the series of standard cables of 24 A.W.G. was 0.041 inch and for 26 A.W.G., 0.033 inch; and the aim in manufacture is to produce an insulation as uniformly close to these dimensions as possible. These diameters are measured by a volume displacement method. Short samples, as representative as possible of the wire under consideration, are inserted for a given distance into a small bore tube of mercury and the displacement noted. The gage is calibrated so that mean diameters are read directly on the scale.

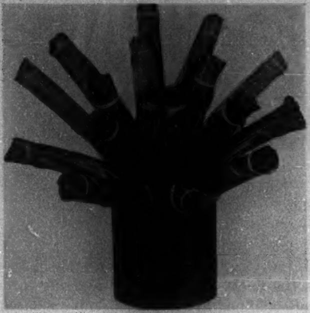

Fig. 7—Section of 1,818-Pair 26 A.W.G. Cable Showing Units Separated

The above specific sizes of pulp insulated conductors apply only to cables designed for a particular set of characteristics. As in the case of ribbon paper cables, the amount of insulation for a given gage of conductor may be varied within reasonable limits, so as to produce cables of other characteristics.

*Electrical Characteristics.* It was reasoned that pulp insulated cables would probably be inherently higher in mutual capacitance than similar sizes of paper ribbon cables because, considering the insulated wire itself, in the case of helically applied strip insulation the volume of air beneath the paper is about equal to the volume of the paper itself, while for pulp insulation there is very little air space between the insulation and the wire. This fundamental difference could be somewhat compensated for, however, by the introduction of more air into the spaces between the fibers of the pulp insulating medium than is found in the paper ribbon itself, but it was not expected that it would entirely neutralize the effect of lack of air space next to the wire. It was appreciated, however, that the aim should be to get as low density insulation as possible still consistent with obtaining a continuous, flexible, and strong covering on the wire and emphasis was placed on this phase from the start of the development.

The very first experimental cables manufactured compared favorably in mutual capacitance with corresponding sizes of strip paper cables. The wire was insulated in a manner resulting in an apparently well centered, round insulation and the covering was low in weight of fiber per unit volume. The insulation after being formed around the wire was quickly dried in a hot tube resulting in less shrinkage and tightening down around the wire while the moisture was being driven out than if slowly dried. The insulation was unsatisfactory, however, from a continuity and tensile strength standpoint and could not be considered as suitable for commercial cable.

Special effort was then directed towards producing an insulation better mechanically, with the result that the early commercial cables were satisfactory in this regard but were from 20 to 25 per cent higher in mutual capacitance than the standard ribbon paper cable. This impairment in transmission efficiency was considered prohibitive for cables to be used for interoffice trunks and was definitely objectionable for any class of service. However, the indicated savings in cable first cost warranted continuing the development, and over a period of years marked progress has been made in reducing this excess of capacitance and yet retaining an insulation sufficiently strong and flexible to handle with reasonable satisfaction in the fabricating of the cable and installing it in the plant. Fig. 8 shows graphically the progress that has been made in reducing the mutual

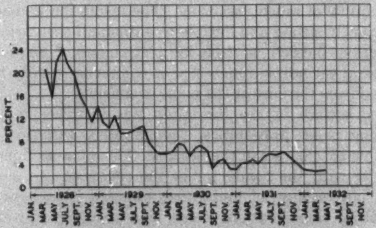

Fig. 8—Curve Showing Improvement in Mutual Capacitance Since Early 1928

Per cent by which capacitance of No. 24 A.W.G. pulp insulated cables exceeds that of ribbon capacitance of 24 A.W.G. cable since early in 1928. Although a substantial improvement has been made in lowering the mutual capacitance to within less than 4 per cent of the corresponding ribbon paper cable, a further reduction would have considerable value, warranting more effort in that direction. For 26 A.W.G. cable the excess in capacitance is even less than for 24 A.W.G., and furthermore, it is not so objectionable from a transmission standpoint as in the case of the larger gage.

The principal factors which have brought about this reduction in capacitance are improvements in the treatment of the pulp itself, refinements in machinery operation to permit the use of a lower density covering on the wire, the more rapid drying out of the moisture from the pulp resulting in less shrinkage of the insulation on the conductors and the producing of more nearly round and better centered insulation. Of these factors perhaps the one having the greatest effect on lowering the mutual capacitance was that of improving the out-of-roundness of the insulated conductors. In studying this phase of the problem, advantage was taken of the effect of flatness of the insulation on the component parts which make up the mutual capacitance. The mutual capacitance of a pair of wires is composed of the direct capacitance between the two wires augmented by a series arrangement of two other direct capacitances, one from each of the two wires to the grounded group consisting of all other wires and sheath. As two wires with oval shape insulation are twisted, there is a decided tendency for two flat sides to stay together resulting in the average separation of wire and mate being less than where circular sections are involved. To determine accurately the degree of out-of-roundness representing the average condition throughout a length of cable by mechanical means is next to impossible, whereas the direct capacitance between wire and mate automatically integrates this condition. Measurements therefore are made of the component direct capacitances and their ratio used as a sensitive indicator of the effect of flatness of the insulation on the mutual capacitance. By using the ratio of capacitances the cable length error is eliminated and accurate determination can readily be made on short lengths of cable.

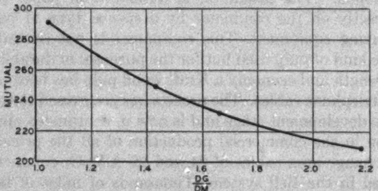

FIG. 9—CURVE SHOWING MUTUAL CAPACITANCE VERSUS DIRECT CAPACITANCE TO GROUND DIVIDED BY DIRECT CAPACITANCE TO MATE

As illustrative of the above relation there are given in the following table and curve, (Fig. 9) data which were obtained on four short lengths of pulp insulated cables which so far as was known differed only as regards the lack of symmetry of the insulation.

Mutual Capacitance *vs.* $\frac{\text{Direct Capacitance to Ground}}{\text{Direct Capacitance to Mate}}$

Average value in $\mu\mu f$.

| Sample | Mut. | $D_M$ | $D_G$ | $D_G/D_M$ |
|---|---|---|---|---|
| 1 | 292 | 187 | 201 | 1.07 |
| 2 | 250 | 144 | 207 | 1.42 |
| 3 | 233 | 126 | 209 | 1.66 |
| 4 | 206 | 101 | 221 | 2.19 |

The alternating-current mutual conductance follows the trend of the capacitance, resulting in the ratio of conductance to capacitance at a frequency of 900 cycles per second being somewhat higher than the standard ribbon paper cable, but not of a magnitude such as to introduce any serious transmission loss for these fine gage circuits. The direct current insulation resistance is of the same order as that of strip paper cables.

The dielectric strength of the insulation is ample, being somewhat higher on the average than that of similar strip paper cables. A rather extensive series of mechanical tests comparing pulp and ribbon types of insulated cable under controlled conditions simulating those met with in actual installation, showed that the pulp insulated cables remained superior to the ribbon cables as regards dielectric strength but that under extreme loads they would not withstand quite as much stretch as the ribbon insulated cable without mechanical damage to the insulation.

*Installation Features.* No new features are involved in installing pulp insulated cable except in the splicing of the conductors after the lengths as supplied from the factory have been placed in position in the plant. This operation, however, is a considerable factor in the total time of the installation procedure because in a not unusual run of a mile of an 1,818-pair cable, there may be as many as 40,000 joints to be made involving the stripping of twice that number of ends of insulated wire preparatory to joining the copper conductors.

Immediately upon removing the lead sheath from the ends of the cables thus exposing the dry insulation to the atmosphere, absorption of moisture rapidly takes place. It is customary therefore to boil out the ends of cable with paraffin wax before starting the splicing operation. With strip insulation this wax also aids in preventing the insulation from unfurling. It was found that even the most flexible pulp insulation so far produced, when impregnated with unmodified paraffin would not withstand satisfactorily the handling incident to splicing at low temperatures. A softer and more lubricating type of compound is required and a suitable combination has been found by adding paraffin oil to the paraffin wax. Different proportions of oil and wax are used depending upon the temperature at the time of installation and the compounding is done at the point of splicing. At an atmospheric temperature of about 75 deg. fahr. no oil is required and below 10 deg. fahr. about half oil and half wax makes a suitable compound with proportionate amounts of oil for intermediate temperatures.

In starting to make a splice, the insulated conductors are brought together in proper position, given a sharp crossover, the wires cut off so as to give several inches of free end, the insulation broken at the crossover and then stripped off the ends. Thus the ideal insulation is one which when waxed, can readily be parted at the crossover and when broken will slip freely along the wire, yet will withstand considerable bending and folding at other places in the splice without breaking. Pulp insulation tends to cling to the conductor somewhat more than a paper tube of strip insulation and although there is considerable variation in this characteristic in the product as now manufactured, it is sufficiently under control so that with a small amount of experience a splicer applying his usual technique is able to handle even 26 A.W.G. wire with little breaking of the conductors.

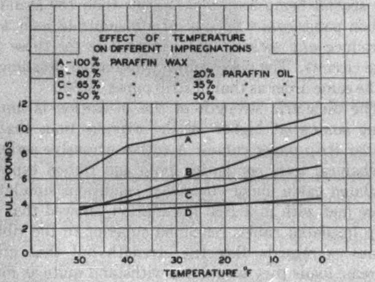

Fig. 10—Curve Showing Effect of Temperature on Pull Required to Strip Insulation Impregnated with Various Wax and Oil Mixtures

Fig. 10 shows the stripping characteristics of typical pulp insulation on 24 A.W.G. conductors impregnated with compounds of different proportions of paraffin wax and oil. The pull required to strip the insulation from a few inches of wire is plotted against atmospheric temperature and shows the benefit of the higher percentage of oil particularly at the lower temperatures. There is, of course, with pulp no raveling of the insulation and the cotton sleeves which are used to insulate the joint, slip over the ends of the wires rather more readily than for the spirally applied paper. Thus the overall time required for joining a given number of pairs is practically the same for the two types of insulation.

An unbleached pulp is used and the natural brownish color of the Kraft stock results in less sharp color distinction for the different groupings of pairs than where ribbon insulation is used. However, by simplifying the color code so as to require only red, blue, and green, besides the natural color, sufficient contrast in the shades is obtained so that there is no difficulty in distinguishing colors in the splicing operation.

## POSSIBLE APPLICATIONS

This work was undertaken primarily to develop an insulation for use in exchange area cables and efforts have been confined largely to this phase of the study. It is possible to vary the characteristics widely by changes in the raw materials, process, and subsequent treatment; other fields of use are being considered.

Pulp insulation is being used as sleeving for lead-in wires in some apparatus at the present time. For this purpose the insulation is made on 19 A.W.G. wire, stripped from the wire and cut in short lengths. It has proven quite superior to the old paper sleeves rolled by hand over mandrels.

Preliminary tests have indicated that there may be a field for the use of this type of insulation with certain modifications for switchboard wiring, terminating cables, and some kinds of coils.

## ECONOMIES

Preliminary cost figures indicated that this process offered the possibility of a considerable saving over the ribbon process. These predictions have been verified by actual machine operation extending over a period of more than three years. The savings are made possible by the low cost of Kraft pulp as compared with manila paper and by the elimination of the intermediate paper making, paper slitting, and handling operations.

## CONCLUSIONS

A new type of insulated wire which is considerably cheaper than paper ribbon insulation has been developed. The insulation is formed from paper pulp directly on the conductor by a special type of paper making equipment. This equipment is not critical to the kind of pulp used but for the purposes of durability, strength and economy a Kraft wood pulp has been used in telephone cables. The process has progressed through the development stage and is now in continuous operation in the commercial production of all the principal exchange area cables of 24 and 26 A.W.G. conductors used in the Bell system. Thousands of miles of lead-encased pulp-insulated cables, ranging in size from the smallest consisting of 11 pairs to the largest consisting of 1,818 pairs, are now giving satisfactory service and because of the substantial economies which the construction promises for the finer wire cables, attention is being directed toward its possible application to larger gage cable conductors and to its use as an insulating medium for other electrical circuits.

## Discussion

**W. A. Del Mar:** Has this insulation flexibility when applied in heavy layers such as 50 mils or over? The paper closes with a suggestion of new applications. Have any of these materialized in the interim since the writing of the paper?

**Robert J. Wiseman:** What is the nature of the wood pulp that the authors are using, that is, is it spruce fiber? Also, as a result of this method of insulating the conductors and assembling, we should get a more firm cable than the usual method of making telephone cable, namely, a certain degree of softness of the cable. At the present time, antimonial lead is used for the lead sheaths of the telephone cables. Have the Western Electric considered using pure lead for these cables for the cases where the cable is drawn into duct? Of course, with aerial cable, they would continue to use antimonial lead.

**L. S. Ford:** Additional points on cable design emphasizing those touched upon in the paper, were brought out as follows:

Up until about 5 years ago, the largest number of pairs in a cable was 1,212. This cable was laid up in the usual manner of reversed concentric layers. Need was felt for a cable of still larger number of pairs and the 1,818, strip-insulated, 26-gauge cable was developed employing the novel idea of first laying up the pairs in bundles or units of 101 pairs and then stranding these units together into a cable. Mechanically, this makes a very satisfactory construction for such a large number of fine wires, enabling the obtaining of a cable which will handle well with little take-up in the stranding. Also since it is a common arrangement to have color groups of 101 pairs each, having the color groupings entirely separated in the cable, layup is of advantage. Pulp insulated wire seems naturally to fit very nicely into this unit idea and the construction has been standardized for 24-gauge as well as 26-gauge pulp cable and is just being applied to 22-gauge pulp cable.

Pulp has not as yet resulted in a new line of cable but in a new type of an existing series of No. 24 and No. 26 exchange area cables which are lower in first cost and compare very well in quality with the ribbon insulated cables which they displace. That is, in the cables so far standardized, the idea has been to make the pulp cable match as nearly as possible cables which had been developed with strip insulation, the gain in cheaper construction and the specific dimensions of pulp insulated cable given under the heading, Cable Design, apply of course, only under these conditions. As stated in the paper, pulp admits of a considerable range of values in weight and diameter and no doubt, advantage will be taken of these in the future which will likely result in an entirely new type of cable.

Some of the principal questions asked were as follows:

1. What are the merits of Jack Pine *versus* spruce as a stock for pulp insulation?

2. What flexibility could be expected from a wire insulated with a thick wall of pulp?

3. How does the wall thickness of pulp compare with strip insulation?

4. Because pulp cables are harder, could not pure lead sheath be used instead of lead antimony sheath?

5. Why was not the core impregnated with some material, such as paraffin?

Answers to the above questions follow:

1. Spruce Kraft is a cleaner, stronger and more expensive pulp than Jack Pine Kraft. It works somewhat better on the machine and has particularly good sheet forming characteristics. This tends to give a better insulation from the standpoint of appearance and uniformity, but experience of several years has indicated lower capacitance in cables made from a Jack Pine Pulp and as this quality is of prime importance, Jack Pine is considered standard at present. This capacitance difference has so far not been explained by the fiber characteristics.

2. A thick wall of pulp would have the tendency to be rather stiff and inflexible, especially when dry and would not admit of being bent on a short radius without injuring the insulation. It would not be as flexible, as for example, an insulation of the same wall thickness of cotton servings.

3. For 24-gauge wire, as an example, the common thickness of strip paper is 0.0025 in., the paper is applied helically with appreciable overlap and with a considerable air gap between it and the conductors so that its mean diameter, as it is insulated, is of the order of 0.045 in. Correspondingly, 24-gauge pulp covered wire is insulated to a diameter of about 0.041 in. with practically no space between the insulation and the conductors, making the wall thickness a little less than 0.011 in.

4. Whereas the insulation on the conductor is more firm for the pulp in comparison with strip, the cable cores as constructed are not particularly different in this respect. Furthermore, the composition of sheath used in Bell System telephone cables, is in no way related to the firmness of the core, lead antimony being universally used for land cable. Lead antimony cable sheath has demonstrated itself to be especially suitable for aerial cables having much longer life than pure lead and costs but little more.

5. For telephone circuits, a dry unimpregnated insulation gives the most efficient dielectric. Impregnations are not required to obtain high dielectric strengths and dry insulation of low density gives the best capacitance and conductance factors.

# Use of Cables for Telephone Distribution Purposes

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***Synopsis.***—*The paper outlines the uses of telephone cable for distribution purposes in typical metropolitan areas, such as Baltimore and Washington. It includes some historical background as to the development of cable and the part it takes in the present overall plant investment. The division of metropolitan areas into central office areas and the various types of distribution are discussed. The engineering procedure followed in the design of cable distributing plant to provide economically a metallic circuit of satisfactory transmission quality to connect each subscriber's telephone with the central office involves the consideration of many factors.*

## INTRODUCTION

IN the early days of the telephone art due to the small numbers of telephones then in service, it was feasible to furnish telephone service by means of overhead wire construction, as shown in Fig. 1. In present day typical metropolitan areas, however, such as Baltimore and Washington comprising from 140,000 to 180,000 subscribers' stations where a separate pair of wires is required to connect each individual line subscriber and every two 2-party line subscriber with the operating center or central office, it is clearly evident that aerial wire construction is out of the question from either a practicable or economical standpoint. The development of cable, therefore, containing large groups of insulated wire conductors in a common sheath having a reasonable maximum outside diameter has been and is the economical solution of the present day telephone distribution problem in the majority of cases.

As far back as 1882, the necessity for investigating the feasibility of underground construction, in advance of the time when the growth of the business in the larger cities would require the wires to be placed beneath the streets, was foreseen and the first considerable underground cable experiment was conducted. By 1892 a maximum of 100 pairs of wires were included in lead-covered cable. Subsequent developments brought this, in the United States, to the present maximum of 1,818 pairs of wires included in a common sheath, having a maximum outside sheath diameter of about 2⅝ inches. The available sizes of cable cover a broad range and generally vary in increments of 101 pairs for the larger size cables and 26 and 51 pairs for the smaller size cables.

In areas such as Baltimore and Washington, the investment in cable plant represents about 25 per cent and 21 per cent respectively of the total telephone plant investment. The following table shows a comparison of the total amount of cable in plant at the end of 1931 with that of 10 years ago.

| | Millions of conductor feet of cable in plant | | |
|---|---|---|---|
| | End of 1931 | End of 1921 | Increase 1931 over 1921 |
| Baltimore | 3,051 | 1,362 | 1,699 or 123% |
| Washington | 3,290 | 1,500 | 1,790 or 120% |

It is interesting to note that the increase in the amount of cable in plant has been appreciable in the past decade. At the present time the average length of cable pair serving each subscriber is 1.1 miles and 1.2 miles in Baltimore and Washington, respectively.

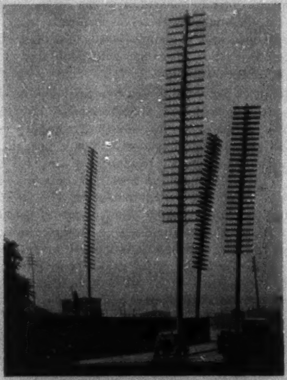

FIG. 1—OVERHEAD WIRE DISTRIBUTION IN THE 90'S

## GENERAL DESCRIPTION OF TELEPHONE DISTRIBUTION SYSTEMS

*Metropolitan Area.* Metropolitan areas (Fig. 2) such as those under discussion must, due to their size, be sub-divided into smaller operating areas, known as central office areas, each containing an operating center at or near the wire center. The central office may be defined as that part of the exchange plant housed in one building while the wire center is that location at which the cost for subscriber lines and interoffice trunks will be at a minimum. The choice of the number of

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exchange areas and locations of the centers is the result of economic studies involving population trends, community of interest, volume of traffic, expected growth, first cost and annual charge comparisons, etc., generally based on a long term program of from 18 to 20 years. It is usually uneconomical to serve a city having a population of over 100,000 from one center because of the long circuits necessary to reach the more distant subscribers, with the resulting use of costly larger gage cable conductors to meet transmission requirements. On the other hand it is equally uneconomical to go to the other extreme and set up a large number of operating centers which require heavy initial investments in land, building, and central office equipment and consequent large operating costs. A happy medium is to establish sufficient centers to more nearly fit the present condition and care for expectations for growth on a sound economic basis.

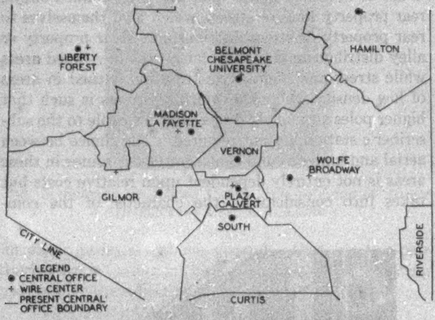

Fig. 2—Section of Metropolitan Area Showing Central Office Area Boundaries and Central Office Locations

Note: Vernon Plaza-Calvert and South will ultimately be served from one office

Cable is used to interconnect the central offices for trunking purposes and to reach subscribers within the exchange areas, the latter usage being the one in which we are particularly interested in this discussion.

*Distribution in a Typical Exchange Area.* The subscriber cables, *i.e.*, the cables connecting the subscriber with the central office, terminate in the central office on the main distributing frame (Fig. 3) where the cable pairs cross-connect to cables which extend to switchboards and other central office equipment. These terminating cables enter the central office through what is known as a cable vault (Fig. 4) generally consisting of a space apportioned off in the basement under the main distributing frame to permit orderly racking of the cables and to provide adequate space for working on the cables, such as splicing. Cables radiating from the central office are generally underground at least in the main feeder routes through areas of heavy subscriber line density, in congested sections, and in locations where franchise requirements or rights-of-way and physical difficulties will not permit overhead construction. Underground feeder cables are connected at their outer ends to the various types of distributing plant such as aerial, block or house cables, dependent upon the type of area to be served.

Fig. 3—Termination of Outside Cable Pairs in Central Office at Main Distributing Frame

Fig. 4—Cable Vault

Exchange areas are of two general types, namely the downtown business and the residential, based on development characteristics and type of building construction. From a telephone standpoint the business areas comprise built-up blocks including department stores, apartment houses, hotels, office buildings, manufacturing plants, warehouses, large retail stores, etc., where the station density is relatively high. The residential areas, on the other hand, are those less densely occupied. They may contain some neighborhood business and may have either the high or the medium class of residences predominating.

*Downtown Areas—Main Feeders.* The cable plant in the downtown area includes a large number of feeder cables, serving both the downtown area itself, and the residential areas beyond. The larger size cables containing the finer gage conductors are placed nearest to the central office to permit the maximum efficient usage in the area of greatest station density and to utilize the minimum number of cables and ducts in the subway. The physical aspects of convenient cable handling and construction features limit the conduit sections in main line subways to about 650 feet. Subway sections are often shorter than this, however, due to lateral branches, to distributing points or to the particular design of the subway system to meet the physical problems encountered, such as layouts of streets or alleys, changes in grades, etc. Cable sections in the main line subway are made continuous by splicing them together in the manholes. Where branch or lateral cables (extended from a manhole) are to be terminated a cable stub is used, which consists of a short piece of cable, one end of which is spliced to the main cable and the other end spliced to the branch cables. The purpose of the stub is to provide a means of adding to or rearranging the branch cables without opening the main cable splices, an objectionable procedure due to causing possible cable troubles and future costly rearrangements.

Fig. 5—Aerial Cable Distribution in Residential Area

*Block Areas.* Branch or lateral cables connect the main feeder cables with the block, house or aerial cables which distribute within the block or blocks or within the buildings in the block. Cable used for overhead distribution consists of the same type of material as is used for underground construction and is termed "aerial" when it is strung on poles, "block" when attached to building walls, etc., and "house" when used for distribution within a building as shown in Figs. 5, 6 and 7.

Block cable distribution is generally considered in areas of high station density such as financial, mercantile, hotel and apartment districts. Since block cable is attached to building walls a large portion of it with its associated terminals is often in inaccessible locations and expensive to maintain. This type of plant does not possess the flexibility of aerial plant, and is subject to frequent rearrangements whenever any building changes are made.

*Residential Areas.* While some block cable distribution is necessary in the congested and neighborhood retail section of residential areas, the majority of the areas are served by aerial cable. The residential development is generally of the row house, semi-detached house or detached house type with well defined alleys, rear property lines or streets which lend themselves to rear property or street distribution. Rear property or alley distribution is used in fairly well developed areas while street and highway distribution is used in areas of low density where the width of streets is such that higher poles and longer drops from the cable to the subscriber's station are not required. The choice between aerial and underground cables for feeder routes in these areas is not entirely dependent upon relative costs but takes into consideration the character of the community, period of usefulness of aerial plant, flexibility of aerial plant, permanency of underground plant and expected growth, bearing in mind that pole lines are generally designed to carry not more than two maximum sized cables.

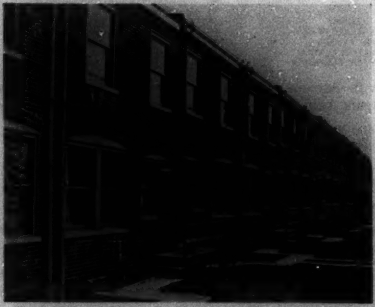

Fig. 6—Block Cable Distribution in Residential Area

In the more expensive residential developments there is often, in addition to the lack of satisfactory locations for overhead distribution, a desire on the part of the property owner or the developer for underground distribution to improve the general appearance. For this type of construction cable suitably protected from soil erosion is buried directly in the ground without the use of conduit. Buried cables are generally located along rear property lines, along the edge of roadways or under sidewalk parkways, between the footway and the curb, and terminations are made by means of small terminals either in small underground concrete splicing boxes or in short pedestals above ground. One- or two-pair buried branch cables are used to connect the distributing cables with the subscribers' premises.

Fig. 7—Section of House Cable Run in Loft of Large Government Office Building

## Cable Plant Design

Problems involving cable plant design are relatively complex as compared with those for overhead wire distribution. Facilities must be provided to care for initial requirements and in sufficient quantities in the proper location to care for expected growth in the most economical manner. A complete system of records continuously maintained is absolutely necessary as basic data for successful design. The more important features embodied in economical cable plant design are given under the following three headings.

*Transmission.* The proper gage and type of distributing cable plant determined for any central office area is based on the maximum allowable loss in the distributing plant in that office area. The allocation of losses between the distributing plant and the trunking plant is determined by economic studies, made from time to time as changing conditions warrant for each exchange area. As a result of these, the permissible limit of subscriber's loop, that is, the permissible total of transmitting and receiving losses are established for the subscriber's station equipment, the pair of wires connecting the subscriber's station to the central office and the associated central office equipment. The central office equipment loss is practically fixed except for certain cases where lines require special equipment, but the loss between the central office and the subscriber's station can be controlled by varying the gage of the cable pairs used. Also several types of subscriber's station equipment are available, some of which are more efficient than others. The design of distributing plant, therefore, involves the choice of the proper gage of cable conductor and type of subscriber's station equipment to most economically bring each subscriber within the loop limit of the exchange area involved. Fig. 8 shows the gage limits for various central office loop limits. The gages of conductors commonly employed in distributing cable plant are 26, 24, 22, and 19 or a combination of any two. The smallest gage conductors consistent with the allowable length of loop are used as a permanent and most economical arrangement in feeder and distributing plant nearest to the central office; however, larger gage conductors are sometimes used as a temporary expedient to defer placing additional cables in feeder and distributing plant nearest to the central office, and at other times to defer placing additional cables in feeder routes until relief is neces-

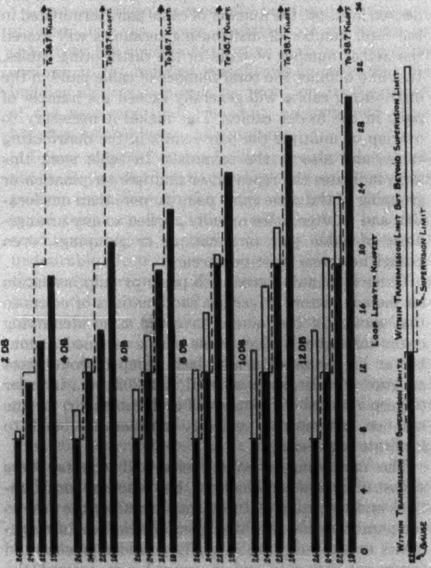

Fig. 8—Gage Limits for Various Central Office Loop Limits Nos. 1, 10, 11 or Panel Type Office—Local Connection

Handset and anti-sidetone station circuit sary. Combinations of two gages are often used to effect economies in areas between the limits of these gages by making the fullest use of the smaller gage conductors.

*Flexibility.* Certain groups of pairs or complements are terminated at frequent intervals throughout the cable length to provide for wire connection to the subscriber's station by means of splicing to the group of cable pairs to be terminated, small distribution terminals ranging in size from 11 to 26 pairs. The location of terminals, either on poles or building walls, is determined directly by the number and locations of stations to be served and the relative economy of establishing terminals as compared with paralleling the cable with aerial wire for short distances.

It is quite obvious that in order to provide cable plant economically and have points of termination available to care for either individual or party line service at any desired location, the number of cable pairs terminated in the total number of distributing terminals will exceed the actual number of pairs in the distributing cables. In a like manner the total number of cable pairs in the distributing cables will generally exceed the number of pairs in the feeder cables. This makes it necessary to overlap or multiple the pair counts in the distributing cables and also in the terminals. In cable work this term indicates the repeated or multiple termination or grouping of the same cable pairs at more than one location and is often more broadly applied to any arrangement of cable pair terminations or groupings, even though no actual repetition occurs.

Cable is manufactured with paper or pulp insulation on the conductors in various combinations of colors so that groups of conductors have the same identifying colors throughout. Each cable pair is assigned a number at its termination and each group of conductors assigned a count, such as 1-101, 102-202, etc., in order to keep a record of the usage of each cable pair, for line number assignments, splicing, maintenance, and to facilitate engineering.

The multipling of cable pairs and counts offers almost unlimited combinations, but practical considerations and operating features usually narrow the field to comparatively few feasible plans. The choice of arrangements must, therefore, carefully consider present and future requirements and in general aim toward the following objectives:

1. Terminate all cable pairs to make them available where they will be needed.
2. Terminate all cable pairs to conform with plans for future relief.
3. Minimize unavailable cable pairs.
4. Make the same cable pairs or count available a sufficient number of times to permit the best possible use of the circuits.
5. Permit simple records, facilitate line number assignments, fault location and trouble clearing and simplify engineering of facilities.

In designing multipling, it is necessary to start with the distribution terminals and cables where requirements are fairly definite. The sizes of the cables having already been determined and estimates made of the ultimate number of stations to be concentrated at each terminal location; the terminals and distribution cables are grouped to the best advantage. The basic principle in this operation is to apportion the available cable pairs to the several terminals in accordance with the number of stations the terminals will serve, due regard being given to the provision of overlap of terminal counts for purposes of flexibility and association of party line stations.

In the cases where distribution cables or distribution complements of feeder cables initially serve several ultimate areas, the section or complement of cable serving each ultimate area is considered separately and these complements are multipled to the best advantage. The pair counts in the distribution cables are next assigned to the aerial feeders, subsidiary and branch feeders and in the main feeders in such a manner as to use up the entire count of the feeder cable. The method of providing future relief, however, generally governs the manner in which this multipling is carried out to provide a minimum of future cable rearrangements.

In the overall results, the care with which the multipling is designed in the initial layout has an important bearing on the conductor usage and flexibility of the cable plant, on the economy of providing service for new business as required, on the provision of and relief to existing cable plant when capacities are reached.

*Planning New Cables and Provisions for Relief.* The requirement for cable is generally associated with one of the following factors:

(a) To provide for anticipated telephone service in an area where no cable facilities exist.

(b) To supersede existing aerial wire distribution where warranted by demands for additional service, or expectations of growth, or due to physical or right-of-way conditions involving the existing aerial wire construction.

(c) Cable of one type of construction superseded by that of another type due to physical or right-of-way conditions.

To meet the conditions in (a), the immediate requirements together with the expected rate of growth generally determine the practicability of placing cable *vs.* wire. Where any doubt is evidenced, the decision rests on the results of cost studies.

In (b) the relative economies determine the course of action where local conditions are not a factor; however, in both (b) and (c) where unavoidable conditions have arisen since the initial route was established, the best engineering solution, taking into consideration the choice of alternate locations, is the answer to the problem.

A study of the records permits a tentative determination of the area to be served and the route to be followed by the proposed cables. Since the initial design is based upon the requirements for the initial area to be served and certain assumptions as to future action, it is also necessary to select at this time the ultimate area to be served by the proposed cable in order to determine the steps to be taken in the future to provide relief. Deviations from the initial routes selected are sometimes necessary, but in the majority of cases underground routes are pretty generally established and most aerial feeder routes are the outgrowth of preceding aerial wire lines.

The number of conductors or the size of a cable for any specific case is one of the most important features of cable design and is dependent directly upon the maximum fill and economic period of fill. The maximum fill is the total number of pairs in a cable that may be used economically without serious interference with the continuity of the service. The economic period of fill is largely controlled by the expected service life, *i.e.,* the average length of time cables remain in plant, and the method of future relief. When these conditions are known or definitely assumed this factor may be determined from cost studies and in the average case is generally from about ⅛ to ½ of the service life of cable. Cables are diminished in size through the distribution area rather than placed in continuous size in order to minimize the cost of the cable plant and to obtain the most efficient operation without penalizing its flexibility.

### BUILDING CABLE DESIGN

In considering the problem of furnishing telephone service to large buildings, it is quite impracticable and uneconomical to place a pair of wires through the building each time a telephone is required. Buildings of these types are generally given service by means of house cable which is placed in the building during its construction, and provides facilities which will permit convenient and efficient connections of telephones at any location within the building. The house cable system is usually designed to meet the maximum requirements of the building with sufficient flexibility to care for any changes in the relocation of the telephones or for any rearrangements to the building.

These systems usually consist of one or more riser cables starting directly from an entrance cable or from a main cross-connecting terminal or frame, in the basement, and extending up through shafts or conduits of the building. Branch cables on each floor are terminated at suitable distribution points by means of floor terminals, where connections are made to the subscriber's telephones by wires.

The general arrangement of the house cable system is almost identical to the general outside plant arrangement in a central office area in that the riser cables may be likened to the main underground cable, the floor branch cables to the subsidiary distribution cables and the floors themselves to individual blocks or areas along a feeder route.

### CLASS OF BUILDINGS

For the purposes of house cable design, large buildings are put into one of two classifications, depending upon the expected permanency of stations, both as to number and location, as follows:

*Office and loft buildings* in which telephones do not remain fixed either in number or location for any extended period but vary with the requirements of the individual, who will use more or less telephone service according to respective activities; or

*Hotel and apartment houses* in which the number and location of telephones are fairly definitely fixed by the number and arrangement of rooms or apartments in the building and the telephone service required by successive occupants is approximately the same.

### PLANNING FOR REQUIREMENTS

Close cooperation is necessary between the telephone engineer and the owner, architect or contractor in order that the house cable system may be designed to conform to the building layout, and in order that the building plans may include the provision, by the owner, of the necessary shafts, conduit, cabinets and other housings for that house cable system.

Unless suitable housing facilities are provided in advance for accommodating cables and wires and for passing them through the walls and floors, either exposed telephone installations will result in unsightly conditions, subject to possible damage with subsequent undesirable effects on service or extensive costly alterations may be required after completion of the building to conceal effectively all cables and wires. These systems of housing facilities include cable and wireshafts, conduit boxes, molding raceways, underfloor ducts, etc., and are designed to conform to the maximum requirements in common with the water, gas, electric light and power conduits as an integral part of the building. The vertical accommodations (for the riser cables) start from the basement and rise to the top floor connecting at the various floors with horizontal housing facilities, and junctions between cable conduits are effected by means of splicing closets or splicing and terminal boxes whereby complete passage is afforded for cable and wire from the basement to the location of the station.

Consideration is given to the intended present and future use of a building, the character of its location and average rental value in order to design the cable plant to meet the conditions. Experience has shown that maximum circuit requirements have a definite relation to rentable or productive floor area and this relation is the basis for both house cable and housing system design. Pair density factors expressing the relation between rentable or usable floor area and cable pairs provided have been developed for certain cities by an analysis of the use being made of house cable in existing buildings. From these data broad averages have been derived in the form of ranges of the number of riser cable pairs per unit of floor area which would provide liberal facilities for the developments realized. These factors are used in determining the amount of facilities to be provided in any particular new problem by applying them to the rentable or usable floor areas.

## Cable Entrance and Main Cross-Connecting Terminals

The cable entrance point is selected with the object of establishing the shortest satisfactory route from the point of connection with the feeder system. Cables are preferably attached to walls or ceilings rather than to partitions which are subject to removal or changes. The number of entrance cable pairs to buildings not served largely by one or several local switchboards is determined in the same manner as the facilities to be provided within the building. The number of entrance cable pairs in a building having private branch exchange service is designed to meet the requirements of one or several switchboards, that is, provide trunk lines, telephone power lines, and facilities for outside extensions, if any, including a surplus of pairs to insure adequacy and also provide central office feeders for stations other than extensions on the switchboard. In some cases the building entrance cable includes facilities for extensions to the adjacent block plant.

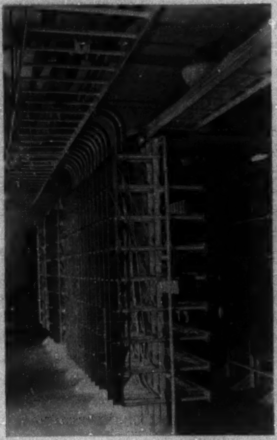

Fig. 9—Cross Connecting Frame in Building

The main cross-connecting terminal or frame, shown in Fig. 9, is usually in the basement at or near the foot of the riser shaft or conduit. The specific location should be determined upon in advance of the building construction in order that the required space may be set aside and the necessary housing accommodations be installed as the building is erected.

## Riser Cables and Housings

Riser cables (Fig. 10) are designed as nearly as practicable to intersect the floors at the wire centers as determined by study of the typical floor plans. Specific location for the riser cable housing is preferably a permanent corridor partition or in the wall of some public place leading from the corridor and easily accessible without annoyance to the tenants of the building.

In buildings having large distribution areas or in which each floor is made up of several distinct distribution areas, two or more riser systems may be desirable, each being used to serve a definite floor area centering about it. In office buildings containing several riser systems, these systems are tied together at certain floors with conduit of sufficient size to house a cable containing enough pairs to permit concentrating the entire floor system on any one riser.

## Floor Cable and Wire Housings

Floor cable and wire housings in combination, afford passage for the telephone circuits from the riser system to the approximate locations of the individual telephones. Cable housings extend more or less directly from the riser to wiring centers on the floor where floor distribution terminals are located and where connection is made with the housings for wire. The floor cable housing system must accommodate a floor distribution cable plant which provides adequate facilities to meet the demand for telephone service on the floor wherever and in whatever quantity it may be. The first step in

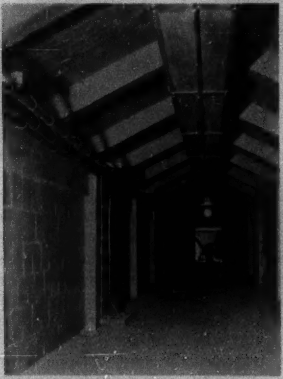

Fig. 10—Section of House Cable System in Large Government Office Building

Showing type of riser cable shaft in loft of building and riser cables the design of the system is the determination of the number of cables including terminals which it will house, their location and size. In small buildings, where the amount of floor distribution is not extensive, the housing system may carry cables and wires together in such raceways as hollow moldings or baseboards. In most buildings, however, separate systems for cable and wire are necessary, although it is usually quite practical and economical to place small cables in lieu of wire in housings intended for wire when special distribution requirements make this desirable.

### CONCLUSIONS

Telephone subscriber cable plant engineering is responsible for the provision, in the best practicable way of the wire plant facilities for rendering telephone service where ever it may be desired within an office area. It also has the responsibility for designing an efficient cable plant. The provision of telephone service by open wires on pole lines would have the advantage that the plant, so far as the wires are concerned, would be operated at a high degree of efficiency. Each pair of wires would be placed as required and extended only as far as required, and little or no idle plant would exist. This is obviously impracticable with cable plant. Facilities in cables must be placed in advance of requirements, and single pairs cannot be ended at the point where they will be used, assuming that this could be determined in advance. Consequently, a considerable portion of the conductors in the cable plant are idle, or spare. It is essential, from the standpoints of both economy and readiness to serve, that this spare margin be maintained within recognized limits. This is a function of cable plant engineering, the control being through the selection of proper sizes of cable and in the provision of flexibility as by cross-connection, multipling, etc., as discussed in the body of the paper.

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## Discussion

**J. A. Cadwallader:** In connection with the buried cable distribution a description of a system recently installed in a high class residential development near Pittsburgh, Pennsylvania, may be of interest.

The development embraced an area of approximately 30 acres subdivided into 155 building lots which were irregular in shape and fronted on curved and winding streets. The land company was desirous of eliminating aerial plant from this development and approached the utility companies with that end in view. The results of cooperation between the Telephone Company and the development company resulted in the design of a buried cable distributing plant involving the following:

(a) The land company reserved a 10-ft strip along the rear property line for the utilities, provided the trench for the cable and excavation for the splicing boxes.

(b) The individual property owners provided a conduit from the house to the nearest splicing box.

(c) The Telephone Company furnished and installed tape-armored distributing cable, splicing boxes and terminals and one or two pair lead-covered cable in the conduits from the splicing boxes to the houses for connection with the subscriber's stations as required.

The plant involved included, in addition to the one and two pair lead-covered cable, about 4,300 ft of 26 to 202 pair 24-gauge tape-armored cable and 21 splicing boxes. These splicing boxes were of precast concrete reinforced with wire mesh and about 26 inches long, 16 inches wide, and 18 inches deep with 2 inch walls.

The entire cost of this distributing system to the Telephone Company approximated very closely the estimated cost of an aerial cable job using pole plant jointly occupied with the Electric Light Company.

**L. F. Cromwell:** I should like to emphasize the importance of careful cable pair multipling in the design of the cable plant to effect a minimum plant investment and minimum annual charges, consistent with good service. It must be borne in mind that every dollar invested in plant carries with it these annual charges as long as it remains in plant. It is necessary, therefore, to guard against too liberal provision of plant.

It is in the engineering of the cable layout and in the selection of the types of materials that the real economies lie. The effectiveness and efficiency of an otherwise well designed cable plant layout may be defeated by lack of thorough consideration in the multipling of either distribution or feeder cables.

The selection of a sound multipling system is essential to ensure permanency and to avoid too liberal provision of plant. Such a system also facilitates the maintenance of clear, concise records and simplifies engineering, assignments, and trouble locating and clearing. The efficiency of the cable or cable plant can be determined by a study of the cable usage. One index of cable usage is known as "pair mile efficiency" which may be defined as the ratio of the conductor feet, or other unit length, of circuit required to serve all stations, to the conductor feet, or other unit length, of circuit actually provided in the cable or cable plant. Pair mile efficiency is largely controlled through the selection and distribution of cable sizes and the multipling of cables.

In a well designed aerial wire plant each circuit is extended only to the farthest station on that circuit. Such a plant, therefore, has 100 per cent pair mile efficiency as well as 100 per cent of its conductors in use.

A cable plant must provide many circuits in advance of requirements and the number of circuits can be reduced only at a comparatively few points in the route and not at each point where the capacity of any circuit is filled. Such a plant cannot have either 100 per cent of its circuits in use or 100 per cent of each circuit in use. Careful planning will, however, assist in obtaining and maintaining high efficiencies. The nearest practicable approach to aerial wire plant conditions is in the use of diminishing cables.

When selecting the multipling system it is necessary to anticipate the successive steps to be taken when subsequent relief for the cable plant is required. Permanent relief can be provided either by reinforcing, replacing or dividing the congested cable, while temporary relief can be provided by making cable transfers to remultiple the cable pairs or by the installation of cross-connecting terminals.

For example, in designing a feeder cable, which is to serve initially more than one ultimate area and which will subsequently be relieved by dividing, it is essential to determine the "points of relief," *i. e.*, the points at which the initial cable may later be cut or divided.

If these points are established to meet a definite estimated growth, the multipling of the cable may be so designed that no rearrangement of branches will be required in connection with successive relief plans, unless the actual growth realized differs appreciably in either location or amount from the predicted growth. Such a layout in reality consists of the repeated assignment of the entire feeder cable pairs to the distributing plant in each area, so that when the cable is initially spliced at the "points of relief" into one continuous cable it will be the same as one cable superimposed upon the other with no conflict between cable pairs in use. This superimposing must also provide for a reasonable number of spare cable pairs for future use in all terminals. When relief is required the installation of an additional cable to the "point of relief" will provide separate feeder cables for the two sections of the original cable.

Cable transfers consist of transferring one or more terminals, distribution or branch feeder cables from certain cable pairs in one cable to other pairs either in the same or a different cable. The result of this plan is a redistribution of both existing lines and provision for expected growth in existing cables, thus making idle pairs available where they can be used to the best advantage.

The real test of cable pair multipling is not encountered when the installation is first completed but when service has increased to such an extent that the cable has a majority of its pairs in use. At that time, in some cases, especially when the growth has not been distributed as was anticipated, relief can be provided by cable transfers which increase the flexibility and defer cable extensions or reinforcements.

**C. L. Garrett:** In furnishing satisfactory transmission, not only must the speech be received with satisfactory volume or loudness but factors which may tend to reduce the intelligibility must be considered and allowance for these factors made in the design of the plant. These factors include noise, crosstalk and distortion, and some of them can, to a certain extent, be counteracted by an increase in volume.

There are two general types of noise which cause objectionable interference. One, which is known as line noise, is due to currents induced in the telephone circuit by neighboring telephone and power circuits and the other is room noise. The detrimental effect of room noise is twofold; first it directly enters the ear of the listener thereby distracting his attention and, second, it reaches the transmitter and sets up currents in the station equipment which produce noise in the receiver thereby affecting the intelligibility of the received speech. In a metropolitan area where most of the distribution plant is in cable and the circuits relatively short, room noise is the most important.

As brought out in the paper several types of subscribers' station instruments are available for desk stands, the principal differences being in the characteristics of the transmitters. For use on low resistance subscribers' loops, sturdy transmitters capable of handling relatively high currents are employed. With the increased use of small gauge cables it was necessary to introduce highly efficient ones designed to operate on small current flows. These latter types, however, do not perform well on the short loops and are harmed by too large current flows. In order to control the use of the various types and at the same time bring all lines in an area within the loop limit with the maximum average efficiency and economy, it is necessary to set up zones in which the different types of instruments available are to be used. However, in the determination of a practical zoning system, several things must be considered in addition to the theoretical limits. For ease in administration the system should be simplified as far as practicable by keeping the number of zones to a minimum and selecting simple, readily located, geographic boundaries for them. In addition, the supply situation must be considered and alternate types of instruments prescribed for zones, where this is practicable, in order to provide a suitable field for the re-use of instruments recovered from the plant. To make the information readily available, maps are usually prepared for each central office area showing the geographic zone boundaries and the types of instruments permissible in each zone.

The distributing plant design is usually based on a maximum condition of transmission which all loops in the area tend to approach. Under this condition it naturally follows that the average value of transmission in a central office area is somewhat better than the limiting value. However, the extended use of the smaller gauge cables and the introduction of instrument zoning practises, together with the fact that losses are introduced by the presence of bridged taps, which are necessary in order to have a flexible layout, tend to make the transmission loss of the average loop approach the limiting value. In many cases there are in a central office area a limited number of extra long lines for which special treatment is required in order to provide transmission within the loop limit.

In addition to the furnishing of satisfactory transmission, the signaling and supervisory limitations of the equipment must be considered when designing the distributing plant. In a metropolitan area, the telephone system is operated on a common battery basis, that is, direct current is supplied from the central office over the cable pair to the subscribers' instrument. In order that sufficient current may flow to operate the supervisory relays at the central office, increased expense for special equipment is involved if the resistance of the subscriber loop exceeds a definite value, the resistance of the central office and station equipment being nearly constant. Referring to Fig. 8 of the paper, it may be seen that in some cases the economical use of the smaller gauge conductors is restricted because of this supervision limit and if only transmission were considered it would be possible to extend these gauges for an appreciably greater distance.

# Electrical Testing in a New Rubber-Covered-Wire Plant

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Non-member
and
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## GENERAL

EFFORTS in the past decade to increase plant efficiency have resulted in a trend toward the development of more satisfactory means of testing the insulation of rubber-covered wires in quantity production, than the standard water test.

This has led to the consideration of various means for more rapid testing and to the evolution of direct testing methods to overcome the disadvantages inherent in the water test. These have not been generally adopted as yet however, and this paper therefore deals only with problems related to the testing of telephone wires and the results obtained.

## PURPOSE OF TESTING

The purpose of any electrical test is, of course, to locate such defects or potential defects as might cause failure in service. A satisfactory insulated wire from an electrical standpoint is one which will withstand the stresses to which it is subjected in normal service, and which will function over a long period of time without failure due to a defective insulation. To insure such service, tests must be made which will simulate in severity the most rigorous conditions encountered.

So far as telephone wires are concerned insulation defects may show up in either of two forms: (1) as a complete breakdown, or (2) as a low insulation resistance.

Among contributory factors in the development of weakened insulation are:

Presence of foreign material in rubber insulation such as: agglomerates of incompletely mixed compound ingredients, metal pieces, wood, vitreous material, textiles, etc.

Mechanical injuries to insulation including bruises, scraped or cracked insulation, and kinks.

Thin or uneven insulation resulting from process variations or defective equipment.

Holes or blisters due either to air bubbles in the compound or other causes.

## DESCRIPTION OF WATER TEST

The water test requires the immersion of the wire to be tested in a water bath for a minimum period of 12 hours before the test is applied.

This insures that the entire surface of the insulation is in contact with a conducting medium, and also that the water will have penetrated to the point in the insulation which would be most subject to breakdown or failure in service.

At the end of the immersion period an a-c. breakdown voltage is applied for a period of seconds, and following ~~this a~~ d-c. insulation resistance test is applied.

The first of these locates any points in the insulation which are sufficiently weak to cause breakdown in service, while the second determines whether the resistance of the insulation is sufficiently high to prevent leakage of current that would impair efficiency in service.

The usual method used for testing telephone wires is to apply the water test after the weatherproofing process. However, this test has several disadvantages among which are:

The water test requires a relatively large area for testing equipment.

The twelve-hour immersion period necessitates a large process stock of unfinished wire.

Continuous flow of material is prevented by the necessary delay of storing tested wire during a drying interval.

Separate testing and coiling or reeling operations are necessary, requiring more machines than would be required for a combined testing and coiling process.

The modern trend in manufacturing methods is to plan successive operations so that there are no delays, thus eliminating costly process storage. Combinations of operations with reduced machinery investment are also of prime importance.

## ENTRY OF WESTERN ELECTRIC COMPANY INTO WIRE MANUFACTURE

Several years ago an investigation was undertaken by the Western Electric Company to determine the possibilities of producing rubber-covered wire with a view to establishing improved methods of manufacture, thereby reducing the cost of telephone wires to the Bell System.

As a result of this investigation a new and faster method was developed, which combined the rubber insulating and vulcanizing processes in one continuous operation.

Prior to that time wire was insulated, packed in soapstone to prevent its sticking together, and was either coiled in pans or wound on drums, preparatory to a lengthy vulcanizing operation.

The radical departure of continuous insulation and vulcanization with its consequent reduction in operations provided a starting point for investigations to further improve and reduce the number of manufacturing operations.

An entirely new plant was erected so that it was possible to consider the most effective layout of equipment,

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*Western Electric Co., Inc., Baltimore, Md.

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the best material handling methods, and the most economic storage plan, as well as to develop new machines and process combinations.

Among the processes which were studied to effect a simplification of operating methods the old plan of separate testing and coiling appeared to offer a fertile field for improvement as the water test and subsequent coiling operation were obstructions to the straight line production plan. It was evident that numerous advantages would accrue from the elimination of the water test and the combining of the testing and coiling operations if a quicker and more direct method could be substituted.

Fig. 1—General View of Spark Testing Equipment

The ideal test for this purpose would be one which would eliminate the following:

The necessity for accumulating stock during the testing and drying periods.

The relatively large area required for the application of the water test and the subsequent coiling operation.

The necessity for separate testing and coiling operations requiring two groups of equipment.

Before starting the development of a new testing process, the field of commercial testing equipment was carefully surveyed to determine whether any existing system could be located that would be adaptable to these plans.

The results of this survey and our own preliminary tests indicated that the equipment being introduced in several manufacturers' plants to locate and patch defects at the depanning operations could be modified and developed to fit our needs.

This equipment is of the dry or direct testing type which impresses a high a-c. voltage upon the outside of the insulated wire whose conductor is grounded. Thus the passage of a weak spot in the insulation through the high-voltage zone results in the formation of an arc from the electrode to the grounded conductor, causing a surge and the actuation of control apparatus to stop the passage of the wire and operate audible and visual signals.

The high a-c. voltage is obtained by means of a specially designed transformer of relatively low power and a condenser in the high-voltage circuit raises the commercial 60-cycle frequency to one of several hundred cycles when this circuit is suddenly closed.

The surge resulting from the arc at the passage of a defect through the electrode actuates the control apparatus in the low-voltage circuit in the manner described above.

The voltage is impressed on an electrode approximately five feet in length through which the wire passes before being coiled. The overrun of the wire due to the inertia of the supply reel as the solenoid brake is applied to stop it carries the defect beyond the electrode where it is accurately located by means of a hand electrode moved along the wire by the operator.

At the time of our investigation this equipment had not been used as a substitute for the water test and an extended development and trial period was necessary, to be sure that defects could be effectively located.

It should be noted that this test does not apply a direct check on the insulation resistance of the compound, but functions primarily to break down any weak spots in the insulation.

A trial unit was obtained which incorporated such features as were apparently required, although it was realized that adaptation to our process would probably involve a number of rearrangements and changes in the mechanical features.

Fig. 2—Spark Testing Electrode, Stop Counter, Combined Wire Distributor, and Fault Locator

The testing transformer of this unit was supplied with secondary voltage taps ranging up to 15,000 volts, and after preliminary trials at various voltages it was determined that the critical voltage for No. 17 bronze parallel drop wire, upon which the tests were being conducted, was between 5,000 and 10,000 volts.

No. 17 BP drop wire consists of two insulated No. 17 gage bronze conductors laid in parallel under a single braid of cotton which is impregnated with a standard saturating and a finishing compound. The water test requirements for this wire are as follows:

| | |
|---|---|
| Breakdown | 1,000 volts a-c. |
| *Insulation resistance | 500 volts d-c. |

Tests were, therefore, conducted on the spark tester at the three available voltages, namely 5,000, 7,500, and 10,000 volts. Simultaneously a portion of each day's run of wire was water tested. This insured that the product submitted for each type of test was similar and that the number of defects located by each method would be most nearly comparable.

FIG. 3—RELATIONSHIP OF TESTING AND COILING UNITS

A length of 100,000 feet was arbitrarily set to serve as a basic unit for comparing the relative defects of wire tested by each method.

Data gathered in these tests indicated that the 7,500-volt tap produced results most nearly comparable to the water test for No. 17 BP wire, but in order to more closely determine the proper voltage another unit was provided with transformer steps of 1,000 volts, and further tests conducted at 6,000, 7,000, and 8,000 volts, as well as confirmatory checks at 5,000 and 10,000 volts.

The second set of data, based in each case on results from 1,000,000 pair feet of wire or more indicated that a 7,000-volt spark test located approximately the same number of defects per 100,000 feet of wire as the specified water test, and that a water retest of this spark test resulted in the failure of only 1.65 per cent of the product.

This was comparable to a failure of 2.75 per cent of originally water tested wire when subjected to a similar retest, and 7,000 volts was therefore established as the proper spark testing voltage. On this basis the spark test was adopted as standard for the testing of No. 17 BP drop wire.

It should be noted that the water test was necessary in establishing the proper spark test voltage to insure equally satisfactory insulation resistance and this test will continue to serve in establishing values for any particular type of insulation.

The adoption of the spark test greatly simplified our plans for the layout of the new plant, but due to special features required for our process, a number of changes was incorporated to improve the efficiency of operation and to increase the unit output, as well as to further reduce the floor space required. Some of the changes made are as follows:

A new electrode was developed incorporating a perforated lower plate or grid, and a pendant chain arrangement. The wire rides in a groove in this grid and the chain conforms to the upper half of the wire, and being free in vertical movement remains in contact with the wire throughout the entire length of the electrode. The lower slotted member permits loose wax to fall through to a hopper at the bottom of the electrode which is emptied periodically. This self-cleaning feature insures the correct test voltage being impressed on the wire at all times with a minimum voltage drop due to the collection of wax on the grid.

The electrode was split in half and the two equal lengths mounted one above the other with sheaves for reversing the wire, thus reducing the floor area required by approximately one half. The electric stop counter was placed directly beneath the electrode thus further reducing the amount of space necessary. (See Fig. 2.)

A fault locator built integral with the wire distributor at the coiling head, was added in place of the hand locator. The new locator is completely guarded to prevent any possibility of shock to the operator. Reference to Fig. 2 shows the present arrangement whereby a system of sheaves permits the placing of the supply stand against the electrode unit and the electrode unit close to the coiling head.

FIG. 4—TWO-HEAD COILING ARRANGEMENT

In order to produce a maximum of tested wire per unit, it was decided that a double coiling head arrangement should be provided so that the operator could tie one coil while another was being tested and wound. The arrangement of two heads at either end of an arm which is capable of rotation in a vertical plane, and on which the coiling head in the operating position could be positively engaged with the take-up driving mechanism was finally decided upon. (Figs. 3 and 4 show this mechanism.) Thus the machine automatically coils, measures, and tests wire continuously, save for the short interval required for the operator

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*With specified megohms at specified temperatures.

to rotate the heads, and connect the wire to the ground clamp on the coiling head for the next coil.

A control system comprising an arrangement of starting and stopping switches and foot control buttons for releasing the solenoid brakes on supply and take-up mechanisms has been adopted to reduce to a minimum any lost motion on the part of the operator.

To provide a foolproof mechanism which would insure that every coil completed was properly tested, the testing circuit and take-up drive mechanism have been electrically interlocked so that it is impossible to rotate the coiling head either by the take-up drive mechanism or by hand, without placing the test voltage on the electrode and fault locator. This is of vital importance in providing a satisfactory test.

In order that the operator may be protected from electrical or mechanical injury, the entire unit has been carefully guarded.

The take-up drive is made inoperative unless the guard over the coiling head is closed; the fault locator is placed in a phenol fiber case which prevents the operator receiving accidental shocks; the electrode is surrounded by a grounded metal guard, and moving members of the drive, as well as solenoid brakes, are properly guarded.

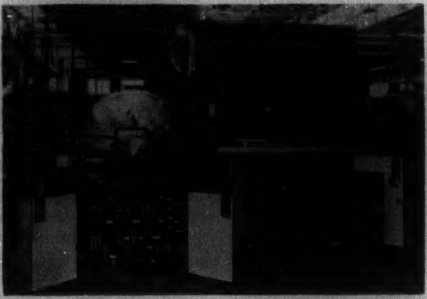

FIG. 5—CONTROL APPARATUS AND MULTI-VOLTAGE TEST BOX

## ECONOMIC FACTORS

The elimination of water testing resulted in several major economies which may be outlined as follows:

1. Reduction in equipment
2. Reduction in floor space
3. Reduction in scrap losses
4. Elimination of process storage

Item 1 is of course of vital importance in the planning of an economical plant, as it affects not only the original expenditure, but also the fixed charges reflected in the operating cost. The saving effected on the original investment represented a reduction of over 60 per cent in the cost of the testing and coiling equipment.

Rental charges applying directly against operating costs were reduced due to the saving represented by item 2, which was reflected not only in the reduced area for testing equipment but also in the elimination of process storage space.

Under the old test method it was necessary to first coil the wire into 1,000 ft. lengths and then water test it, after which the defective coils had to be removed from the water, dried and recoiled to locate the defect. This resulted in the scrapping of a portion of a large percentage of these coils in which the defect occurred near the end, making the short end too short to meet the minimum length requirement of 200 ft. It also necessitated a second operation which was in itself wasteful as it required special recoiling and testing units.

With the new or spark test method the number of short coils which had to be scrapped was greatly reduced, because when a defect occurred it was necessary to cut out only the short section in which the defect occurred and start a new coil. The number of cases where a defect occurred within 200 ft. of the start of a coil was measurably fewer, since no predetermined length had to be maintained.

## FURTHER APPLICATIONS

After successfully applying this test to parallel drop wire, we conducted similar tests on twisted, rubber-insulated and braided wire. The wire in this case was No. 14 hard copper drop wire, which has a 50 per cent heavier insulation than No. 17 BP drop wire, and is comparable in size to No. 14 code wire.

Data were gathered as before, and a satisfactory test voltage established which resulted in the adoption of the spark test for this wire. The voltage was, of course, higher than for the smaller wire, and the success of this experiment indicated the feasibility of spark testing either parallel or twisted wires of various sizes.

It is apparent from the present stage of development of this method of testing that further adaptations are possible which may result in more extensive applications to rubber-covered wires throughout the entire wire industry, with commensurate reductions in the cost of wire manufacture. As previously stated the water test will continue to serve for setting up the proper spark test voltage to insure a sufficient insulation resistance using any particular type of compound, but after this has been determined, using a minimum of equipment, the spark test may be set up to handle the regular production.

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# Discussion

**W. A. Del Mar:** Since the early days of electric wire manufacture it has been customary to give wire a preliminary test by a continuous process. The early apparatus, induction coils operated by direct current and giving a highly unbalanced alternating-current wave of low frequency, was unsatisfactory both because it did not reliably detect weak spots even under the best conditions and because operators sometimes forgot to ground the wire under test. As it became obvious that higher voltages and adequate insurance against open test circuits were necessary, it occurred to me that both of these advantages could be attained by the use of high frequency alternating current. Mr. Lawrence M. Cockaday, then associated with me, designed an apparatus along these lines and it was put to use on an extensive scale in the plants of the company with which we were connected. It was essentially a Tesla coil which gave voltages up to about 20,000 at a frequency of about 200,000 cycles. Somewhat less than half the full voltage was found satisfactory for the ordinary 3/64 in. of rubber insulation and safety to operators was assured by exposing only the high frequency terminals, the remainder of the apparatus being in a closed cabinet.

All wire was tested as it emerged from the tubing machines which applied the rubber insulation to the wire and again after vulcanization as the wire was "depanned" or taken out of the vulcanizing pans. The former test serves to detect faulty application of the insulation or defective stock which is thereupon scrapped. The latter test serves to detect "pinholes" in the insulation which are repaired then and there so that coils of wire of standard length are obtained, which are subsequently tested in water with 60-cycle voltage.

I wish to ask the authors these questions:

1. Do they repair the wire and coil in standard lengths, or do they cut the wire and coil in irregular lengths?

2. Why do they use a frequency of a few hundred cycles when by the use of higher frequencies, shock can be avoided, a spark of greater "searching" ability obtained, and the necessity of grounding the wire avoided?

With regard to the possibility of the spark test superseding the immersion test, the principal difficulty arises from the conditions of inspection by customer representatives. The inspector cannot witness the continuous sparking of thousands of feet of wire. He spends a limited time at the plant and requires a test that can be made in a short time on a large accumulation of manufactured product.

Another objection to the spark test is its unreliability as a detector of flat spots which are much more reliably found by the 60-cycle test in water.

The high frequency sparker as a preliminary testing device is a real help in the production of high quality wire. Its use as the sole test of dielectric strength is in my opinion opening the way to a let-down in quality.

**Robert J. Wiseman:** What is the speed with which the wire travels through the testing outfit? Also, what voltage and time values are used in making the water test? What are the limiting thicknesses of insulation which the authors would consider safe to use on this spark testing method?

**C. W. Protzman:** The answers to Mr. W. A. Del Mar's discussion are given in the following:

1. In our process we cut the wire in irregular lengths. However, repairs could be made if we were required to furnish only standard lengths.

2. As pointed out in our article we tested equivalent quantities of wire manufactured during the same period and under the same process by both the standard test in water and by the spark test, and found that the spark test was slightly superior to the test in water. This was with 60-cycle spark test equipment.

In view of the adequacy of the 60-cycle spark test as demonstrated by our findings as well as some undesirable features of higher frequencies, we did not consider it advisable to design our equipment for high frequencies. Shock is avoided on our machines by provision of suitable guards and automatic interlocking safety devices.

With regard to grounding the wire, it is our belief that this is advisable in order to insure a definite and constant test voltage being applied to the insulation. Means are provided to insure that the wire is grounded during test.

Our manufacturing process with continuous insulating and vulcanizing has greatly reduced the possibility of flat spots. If any flat spots or irregularities occur which would result in an electrical defect these are located by the spark test.

It should be kept in mind that before the spark test voltage is determined for any particular type of wire, a comparative test must be made of the wire with both the standard and spark testing equipment to establish the correct spark test voltage to meet given requirements.

The spark test is inherently a dielectric strength test, and our experience over several years of operation indicates that after the proper voltage is determined as outlined above, wire tested by this method will be of comparable quality to the water tested product.

As previously pointed out, our experience has been entirely with telephone wires, and we are not therefore, in a position to state whether this method of test is directly applicable to other wires.

The following is in answer to Mr. Robert J. Wiseman:

1. The speed of the wire passing through the test unit is 750 feet per minute.

2. The voltage and time values for the water test on No. 17 BP wire are:

| | |
|---|---|
| Breakdown 1,000 volts a-c | time 5 seconds |
| Insulation resistance *500 volts d-c | time 1 minute |
| Time of immersion | 12 hours minimum |

*Voltage at 56 deg-64 deg F.

3. The maximum thickness of insulation tested on our equipment is 3/64 in., and the minimum is 1/64 in.

These represent the sizes of wire which we test, but no data are available to define the machine limitations. It is our belief however, that wider ranges are possible.

# Economic Aspects of Water Power

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***Synopsis.***—*This paper gives a brief survey on the economic relationship of hydro and steam power during the past decade, followed by an analysis of typical hydro power costs, divided into the four components; base cost, incremental capacity, transmission, and tie-in facilities. The value of hydro power is analyzed by comparison with the two main components of steam cost, capacity and energy. The possibilities of increasing installed hydro capacity at low incremental cost are emphasized and a method is described of making such low cost capacity furnish firm peak service on the combined hydro-steam load system.*

DURING the past decade, water power in all those regions of the North American continent where it is employed in conjunction with thermal sources of power has undergone a gradual but pronounced change in its economic relationship to steam power. There are two main components that make up the economic value of water power; capacity and energy. The capacity value of hydro plants, or the cost of procuring equivalent capacity service by other sources of power, has not been measurably affected so far by the advance in the art of constructing thermal plants, but the energy value or the cost of producing energy by other means, has been reduced in recent years to the lowest figure ever encountered.

This downward trend in energy value may be traced chiefly to two causes, namely, the improvements in thermal economy and the declining price of fuel, and in a minor way only to miscellaneous causes such as reduction in maintenance cost and operating labor due to improvements in design, concentration of large capacity in comparatively few units, etc. There is some well warranted expectation that the future trend of average fuel prices will be decidedly upward, but probably not sufficient to overbalance materially the effect of further improvements in thermal economy that may be realized in the future.

Since the total energy output for a given water power site is more or less limited by natural conditions of discharge and head, the gain in energy output due to various refinements in the efficiency of energy conversion is necessarily only of minor importance. It is evident, therefore, that the most fruitful field of endeavor for enhancing the economic value of water power will lie in the direction of (a) reducing the investment cost per kilowatt to a point where the carrying charges will compare favorably with equivalent cost of steam power, and (b) increasing the total amount of economically installed capacity beyond the formerly accepted limits and coordinating the operation of the combined sources so that such additional economic hydro capacity can be utilized to render firm peak service to the power supply system of which it is a part.

The purpose of this paper is to review briefly the parallel developments in the economics of water power in respect to these two main components, energy and capacity, and to give an outline of future possibilities for enhancing the economic value of water power.

## FACTORS CONTROLLING CHOICE OF HYDRO OR STEAM AS SOURCE OF SUPPLY

There are few electric systems in this country supplied wholly by hydroelectric generation, chiefly because it has been economically advisable and often necessary to provide low flow reserve generating capacity by means of steam plants located near load centers. There is no generally accepted ratio of hydro to steam capacity for best economic results, but the optimum proportion for any system is determined by the relative investment costs, fuel costs of steam energy, and the characteristics of system load and water supply. Fundamentally, the benefit derived from the two sources of supply comes from the combination of a low operating energy cost in the case of hydro with a low unit investment cost in the case of steam; while the total investment to carry the system peak may be larger in a combined system than with steam alone, the excess investment is more than compensated by the low cost of energy derived from hydro. The two sources of power should be regarded as supplementing rather than competing with each other. The quick starting characteristics of hydro units, namely, the ability to start them from standstill and synchronize them with the load in a small fraction of the time required for steam units, provides a high degree of standby readiness for emergencies. Hydro units, especially of the low head type having short water passages, are well adapted to maintain system frequency. Hydro pondage or storage can be drawn upon to relieve the steam plants of the task of ironing out discrepancies in the forecasting of system load demands, to save banking of extra boilers and generation by less efficient units, and to facilitate the advance scheduling of equipment for generation as well as for withdrawal from service for inspection and maintenance. Hydro generators are also adapted to no-load operation as synchronous condensers for voltage regulation or power factor correction without consuming much energy or requiring elaborate precautions against overheating or rubbing as in the case of steam units.

## FIRM HYDRO CAPACITY

The best method of operation on a combined hydro and steam system is generally found by scheduling the

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hydro plants for maximum efficiency in periods of deficient water, and for maximum energy output in periods of plentiful water. Operation is simplified by the presence of hydro pondage or storage. Hydro capacity is held available during low flow for instant use in case of emergency at associated steam plants. Hydro always supplies a belt on the system load curve according to water availability such that the largest possible hydro capacity is utilized, thereby operating associated steam plants at improved load factors in periods of deficient water.

That portion of the hydro capacity which under certain assumed conditions (generally coincidence of highest system load demands with minimum flow), controlling the capacity investment for the system as the whole, will render the same capacity service in the upper portion of the system load curve which an alternative steam plant might perform, is called "firm hydro capacity." With large pondage and favorable load conditions, the firm capacity of the first hydro plant connected to a load system may be many times the minimum twenty-four hour power available. The minimum flow energy for a second hydro plant, however, feeding into the same load system, will yield a relatively smaller firm capacity than the energy from the first plant, *i. e.*, the increment gain in firm hydro capacity per unit of hydro energy will decrease with an increase in the total amount of hydro energy available.

## Developments During the Past Decade Favoring Water Power

Certain factors of increasing advantage to hydroelectric development have made possible, and hold promise for still greater usefulness of, numerous hydroelectric projects which would not have been considered economically feasible during preceding years, notwithstanding the higher unit value of energy in those years.

Among these factors, is the present large size of electric utility systems in consequence of natural growth as well as of the interconnection of contiguous load areas. Almost without exception, new large scale hydrodevelopments are made by electric systems which supply their output to metropolitan load centers or to a group of systems covering a regional territory.

The shape of peak of electric system loads is favorable for utilizing a large installed capacity in hydro plant under minimum water conditions, which allows a large capacity value to be allotted to hydro. Especially in the region along the Atlantic seaboard, the sharp peaks of metropolitan load centers, although seasonal and of short duration, may occur simultaneously at the same hour and on the same day. This lack of assured diversity in load demand of interconnected systems, while unfavorable from the point of view of overall power cost, gives pondage equipped hydro plants an opportunity to utilize a greater portion of their installed capacity for firm peak service on the combined load system.

Another feature of large utility system loads has been the annual increase in peak, which has been of such an amount that the entire capacity of new hydro developments has become usable on the peak within a comparatively short time. On the other hand, the minimum system load is sufficient to absorb a large hydro output when water is plentiful in run-of-river plants. Plants which can be developed beyond the continuous flow capacity at a low incremental cost can produce a large volume of low cost secondary energy.

Advance in the art of power transmission has made it possible to transmit large capacities over long distances at reasonable cost, good voltage regulation, and low energy losses. In some instances step-up switching stations at the hydro plants and step-down terminal stations of transmission lines can be developed advantageously as integral parts of interconnection projects, tying together large power systems, which formerly functioned as separate units, into a regional power system extending over large areas. In this manner a dual function is performed by the hydro transmission and tie-in investment, especially on systems which have adopted 230 kv. as standard voltage. The high degree of service reliability of all types of equipment at this voltage has encouraged designing engineers to simplify their system layouts and to rely more on higher mechanical and electrical factors of safety of equipment than a multiplicity of lines and reserve apparatus, all of which had a tendency to reduce investment cost or increase the service value of the hydro projects. Most recent operating experience with high-voltage transmission lines embodying some advanced features of design, has been so satisfactory that lightning proof operation of transmission lines is within the range of possibility at not too distant a future.

At the hydro plant proper, a number of factors have contributed towards the lowering of investment cost, aside from the effect which may be ascribed to lower price levels of structures and machinery. With construction plants laid out for low handling cost and rapid progress, and with careful engineering work applied to temporary structures, flood control, etc., the period of construction has been shortened and substantial amounts are thereby saved which formerly were expended on interest and other carrying charges during construction. Economies in the cost of financing are made possible by the sponsoring or underwriting of major enterprises through existing large utility systems, and few projects are now undertaken for which the market has not been secured in advance at least to the extent necessary to insure the interest on bonded indebtedness with a sizable margin of earnings.

It is possible now to get more capacity out of a given structural space, not only due to increased size of units but also due to higher specific speed of turbine runners and improved design of water passages. Higher speed and improved design of machinery have lowered the cost of main turbine and generator equipment. Auxiliary apparatus has been simplified and its cost decreased.

No appreciable improvement in best efficiency of runners has been recorded during the past decade, at the beginning of which peak efficiencies in excess of 90 per cent had already been reached. However, with the advent of the adjustable blade Kaplan turbine high efficiency can now be secured over a much wider range of loading for low head plants, and the overall efficiency of energy conversion for the plant as a whole has been raised noticeably over that of earlier installations. Testing of models is no longer confined to runners and draft tubes, to observations of efficiency, output, and to studies of the cavitation problem, but extends to every phase of the project from headwater down to the lower end of the tailrace channel. As a result of model tests, more economic designs of spillways, pier and apron sections, flood gates, etc., have been developed. Effective steps have been taken at the newer plants to guard against service interference by trash and ice runs.

### PUMPED STORAGE PLANTS

Pumped storage plants involving specially constructed high- or low-level storage reservoirs, do not play so important a part in the power supply scheme of large systems as they do in continental Europe. Several such projects are under discussion, but only one major installation, a plant built in 1928 on the Rocky River, a small tributary of the Housatonic River, in New England, is actually in service. The plant pumps from the Housatonic River to a reservoir of 68,000 sec-ft-days usable capacity located on the Rocky River. The average yearly runoff of the Rocky River is 17,000 sec-ft-days.

While pumping is done mainly by off-peak steam power, the Rocky River plant provides in addition seasonal storage service to other plants located below on the Housatonic River. The installation of the 24,000-kw. generating unit in the Rocky River plant and the pumped storage reservoir actually added 40,000 kw. of yearly firm capacity to the electric system served by the plant. The efficiency of direct recovery by the Rocky River plant alone is approximately 60 per cent, but on account of the presence of the lower plants the overall conversion economy derived from all plants is raised to nearly 80 per cent.

### DUAL USE CAPACITY INSTALLATIONS

This novel type of development is functionally related to pumped storage plants, being based on the principle of converting low cost off-peak energy into high value peak capacity and energy. It employs the same unit as a turbine-generator and a motor-pump set, without however requiring a specially constructed high- or low-level storage reservoir, conduits or hydraulic control equipment. It is especially adapted to those hydro plants where the increment cost of generating and transmitting capacity is lower than that of equivalent steam capacity and where a substantial overlapping of heads can be readily arranged. The runoff characteristics should be such that, depending on the efficiency of the conversion cycle, the duration of the low-flow stage, during which conversion of off-peak energy into peak energy takes place, is not too great compared with the duration of the excess flow period, during which the dual use equipment produces energy for the system. The above conditions are somewhat interrelated in that in some instances a large saving in investment cost may more than compensate for the extra cost of energy caused by conversion losses during low flow exceeding the gain in output during high flow, notwithstanding the fact that on such a project the low-flow days may greatly outnumber the high-flow days.

The operation of the generator in reverse direction as a motor offers no serious difficulties but the design of the different types of turbines and hydraulic structures for dual use at synchronous speed and the possibilities of variable speed electrical and hydraulic equipment have not yet been developed to such a degree that this simplified regenerative cycle can be readily adapted to those hydro projects where natural conditions of the power site are favorable.

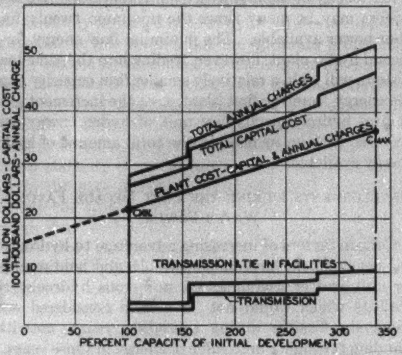

FIG. 1—ANALYSIS OF COST OF HYDRO PROJECT

A great deal has been published in the technical literature, especially in Europe, on the principles and applications of pumped storage predicated in each instance on the employment of two separate hydraulic motors, one for generation and the other for pumping, and in nearly all cases also on the presence of a specially constructed high- or low-level reservoir. The employment of a single hydraulic motor for dual function and the omission of specially constructed reservoirs introduce substantial economies in capital investment, but involve a sacrifice in efficiency of conversion.

Perhaps in the search for the optimum of efficiency, we are inclined at times to throw aside as unworthy of further study, the suggestion that a process which is admittedly inferior from a point of view of efficiency may yet be superior from the point of view of overall economy.

The simplified method of hydro regeneration has not been treated so far in the technical literature. As a proper evaluation of the possibilities of this process is of some importance on account of its effect on the economics of future hydro developments, the principles underlying this method as well as certain empirical results from laboratory and field tests are described in greater detail in an Appendix, including an analysis of those factors that will limit its field of application.

### ANALYSIS OF HYDRO POWER COSTS

There are four main components that may properly be regarded as the cost of hydro power, namely:

a. Base cost of the development, which is more or less independent of the amount of installed generating capacity.

b. Cost of generating capacity, including low-tension switching equipment.

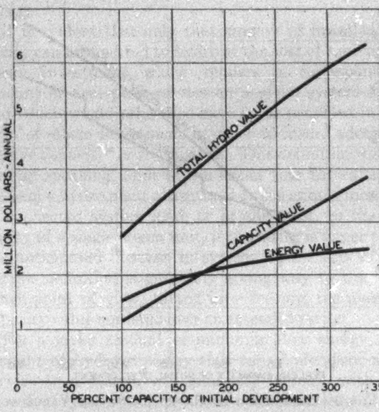

Fig. 2—Analysis of Value of Hydro Project

c. Transmission investment, including step-up transformers and other high-tension equipment at the power house.

d. Tie-in investment, such as step-down transformer and switching stations, underground cables, and other special equipment necessary for delivering hydro power to a distribution system or to a high-tension network.

Until quite recently it had been customary to group the first two components into a single item, "cost of power plant." This practise was usually adequate for the purpose when investigating the economics of existing plants. However, segregation into the two components,—base cost and increment cost, is almost indispensable during the preliminary or project stage of a new development in order to determine the most economic size of the initial and ultimate installation and the part that it should play in the power supply scheme of a territory. The fact that such a differentiation exists, that the two components can readily be segregated and that their relative magnitude as well as their value per unit of capacity furnish a yardstick for comparing one project with another, is one of the characteristic economic features of hydro plants as distinguished from steam plants, where the first component, base cost, ceases to be an important factor after more than one generating unit is installed.

Cost of dam, property, flowage rights, construction equipment and temporary structures, relocation of bridges, highways, railroads, general site improvements, a certain minimum of tailrace excavation, auxiliary station equipment, etc., all of which are more or less independent of the amount of capacity installed, constitute Base Cost. Due to a great variety of causes this cost for almost identical hydraulic conditions of head, average discharge and length of backwater, may show variations of several hundred per cent.

The second component comprises the cost of generating equipment, hydraulic as well as electrical, power house substructure and superstructure, low-tension switching and auxiliary equipment, intakes, control equipment, increment tailrace excavation, etc. It is sometimes called the incremental cost of hydro capacity. For similar hydraulic conditions this second component, expressed in dollars per kilowatt, is almost constant, except for major fluctuations in price levels and for differences in the accessibility of the power site. Even over a wide range of hydraulic conditions it will rarely deviate more than 25 per cent from the average, which is approximately $60 per kilowatt.

Considering the approximate constancy of incremental cost and the great variation of base cost, a full answer to the question whether a hydro plant is a high- or low-cost development, cannot be given unless total power plant costs are segregated into these two components. For purposes of illustration, the values used in Fig. 1 and Fig. 2 have been selected as a representative average for a low-head pondage equipped run-of-river plant, located on the Eastern slope of the Appalachian range.

During the project stage, when only estimated and not actual cost figures are available, this approximate division of cost may be obtained by plotting against kilowatts of installed capacity as abscissa the estimated cost for the minimum capacity (C min.) as well as for the maximum capacity (C max.) that is under consideration. The point of intersection of a straight line, drawn through these two points, with the axis of cost will give the approximate value of the base cost component. As certain structural provisions must usually be made initially to permit expansion to a larger ultimate capacity the actual cost of the minimum capacity installation (C min.) will be somewhat higher than the estimated cost of minimum capacity exclusive of these provisions for future expansion.

The vertical scale in Fig. 1, representing capital cost, can be converted readily into a proportionate scale of annual charges, as the sum total of interest charges, taxes, depreciation, operation, maintenance and other expenses is approximately proportionate to investment. In Fig. 1 the overall rate has been assumed at 10 per cent, based on an average return of approximately 7 per cent on investment. Depending on the method of financing, this overall rate may be somewhat reduced especially during the initial years.

The sum of the first two components represents the cost of the power plant proper, controlled largely by the hydraulic characteristics of head and discharge and by local conditions at the power house site and along the shores of the pond or reservoir. The other two components of cost, transmission and tie-in investments, are controlled by the geographic location of the plant in respect to its potential market and by the opportunities of effecting a physical tie-in to existing lines of distribution networks at a minimum of cost.

Although bearing hardly any relation to plant costs, yet these two components must be fully considered as cost elements for hydro power. It is not infrequent that a low-cost and in every other way seemingly ideal project is uneconomic by reason of excessive transmission and tie-in cost. Conversely, certain other projects may be favored by short transmission distances to load centers, nearness of existing high tension lines, advantageous location of step-down stations in respect to city distribution systems, etc.

In some special cases these two components of costs may become a credit rather than a charge. If, for example, a large power consuming industry is located so close to the power site that it can be economically served at generating bus voltage, there will be a saving in transmission cost compared with supplying power to that industry from a more distant source; or if nearby railroad lines which often follow the course of rivers, are electrified, there may be a distinct saving in tie-in expense not only by reason of the nearness of the electrified tracks but also, in the case of the 25-cycle single-phase system, by reason of employing at the lower speed single-phase hydro generators instead of the customary frequency converting equipment required in connection with 60-cycle steam power.

The above described cases are exceptional rather than average conditions. As a rule, the combined cost of transmission and tie-in investment will appear in the nature of a charge rather than a credit for hydro power. Especially where long distances are involved, such as Boulder Dam or the St. Lawrence Development, the cost of these two components may be equal to or exceed the increment cost per kilowatt of installed hydro capacity. The development of 230-kv. transmission had a tendency, where large amounts of power are involved, to reduce the transmission cost per kilowatt for a given distance, but to increase slightly the tie-in cost.

As extensions are made at the hydro plant the cost of transmission will increase in sharp steps corresponding to the building of additional transmission lines, but the tie-in costs will usually grow at a gradual rate, corresponding to the step by step installation of additional underground cables and other tie-in equipment to keep pace with the increase in hydro capacity.

The annual charges in connection with transmission and tie-in facilities will bear again a proportionate relation to the investment, but at a somewhat higher rate (12 per cent to 15 per cent) than that used for the annual charges of the hydro plant proper.

While it may appear academic to combine at an early stage of the project the estimated cost of the hydro plant proper with the cost of transmission and tie-in facilities which are indirectly dependent upon the marketing of hydro power, yet a tentative forecast of these cost components is indispensable for a preliminary investigation of the economic justification of a project. Instead of adding these two components to the other costs of hydro power, one could subtract these items from the composite value of hydro power, which is analyzed in the section below. This latter method, however, would not give as clear and convenient a graphic picture of the relationship of overall cost and value.

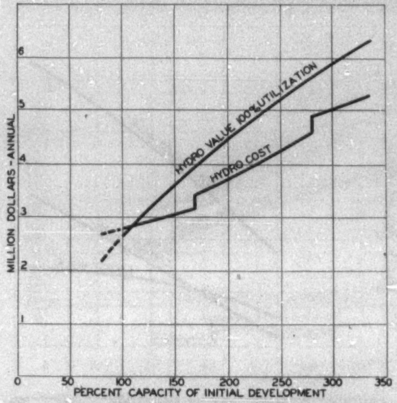

Fig. 3—Comparison of Hydro Costs and Value

## Value of Hydro Power

The generally accepted yardstick for evaluating hydro power is to determine the replacement cost of its two main components, capacity and energy, by the cheapest alternative source of supply, namely steam. Hydro projects that are so situated that they have only a single potential market for their output, are more readily analyzed than those projects which have several possible outlets for power and the operation of which can be so coordinated with the operation of the several steam plants that hydro power renders the relatively most useful, and therefore the most valuable service to the combined system.

Aside from the replacement value of hydro power as measured by the steam yardstick, a hydro plant, especially if located upstream in respect to a series of individual plants on the same river or watershed, may, by proper coordination of power house discharge, add materially to the energy and capacity output of the plants located downstream. There are also a number of other more or less collateral or contingent advantages of hydro power which it would be difficult to express in definite figures. Some of these features have been referred to in a previous section, dealing with the choice of hydro or steam as a source of supply. For the purpose of this approximate analysis, however, all these collateral features are omitted and evaluation of hydro is confined to the two main components of capacity and energy

It is evident that only that amount of installed capacity can be credited to hydro at the cost of equivalent steam investment which renders a corresponding amount of firm peak service on a given system load, and which would otherwise have to be provided in the form of steam investment in order to insure adequate reserve capacity for the system. This definition would, strictly speaking, limit in the initial year the capacity value of a hydro plant of any type to the annual increase in connected system load, or at the most, to the capacity of a single steam unit, if the latter is larger than the anticipated increase in system load. This rather narrow definition is gradually giving way to the long range point of view, taking into account the average capacity value rendered over an extended period.

For a given amount of minimum flow energy, the amount of hydro capacity that can render firm peak service to a system will gradually increase with the growth of system load, provided the load at least in the upper portion of the curve retains approximately the same shape. If additional load areas which heretofore supplied all their requirements by steam, can be tied in to the new hydro plant, the firm peak service rendered to the combined system will be materially increased, provided, of course, that the character of these new load areas is similar as to shape of load curve as those originally served by the hydro plant, or possibly still more favorable for the utilization of firm peak service by reason of pronounced seasonal peaks.

The capacity value per kilowatt comprises, in addition to the fixed charges, *i. e.*, interest, depreciation, taxes, insurance and some general expense, also those items of steam plant operating costs which are more or less independent of the amount of generation. This combined value varies somewhat in different localities. Aside from differences in price levels, it is probably more affected by the size of individual steam units than by any other single factor. Under present day conditions its lowest value is perhaps in the neighborhood of $10.00 per kilowatt and in some instances exceeds $18.00 per kilowatt for medium size, but otherwise modern stations, the average being in the neighborhood of $13.00 which is the value used in Fig. 2.

The energy value per kilowatt-hour comprises, in addition to the cost of fuel and maintenance, only some minor items of operating supplies and labor. Depending mainly upon the price of fuel in the territory, the heat cycle of the station and the relative size of boiler and turbine units, the energy value under present day conditions may be assumed to vary, except in the case of mine mouth plants, from a minimum of around 2.0 mills per kilowatt-hour or slightly less, to a maximum of around 3.0 mills, the average being perhaps 2.5 mills for unit capacities of 50,000 kw. or higher.

This latter value has been used for computing the total energy value of the hydro project analyzed in Fig. 1 and Fig. 2, assuming full utilization of the hydro energy available.

In order to approximate the effect of transmission losses, of capacity reductions by flood stages, drawdown of pond, etc., certain percentage reductions have been applied to energy as well as capacity. For less than 100 per cent utilization of either installed capacity or available hydro energy, the combined curve will drop below the values indicated, the amount of which reduction can be readily determined as a proportionate reduction of the respective component parts.

The composite curves of hydro costs and hydro values have been replotted in Fig. 3 in order to bring out more clearly certain trends frequently observed in connection with major hydro projects serving a large interconnected load system supplied by hydro and steam. During the initial years of operation, hydro will compare less favorably with steam values than during later years. However, there is a reasonable expectation that a hydro plant which has low incremental cost and not unduly high cost of transmission and tie-in facilities will in the long run yield a substantial margin of savings below the cost of steam. In addition, there will be a number of collateral advantages to its credit, which have been omitted in the above graphic presentation.

## Appendix

### REGENERATIVE CYCLE AT PONDAGE EQUIPPED HYDRO PLANTS

### SECTION I

The practise of storing water by pumping into specially constructed reservoirs for the purpose of producing peak power, started over thirty years ago. Compared with electric storage batteries or the storage of energy in heat or pressure accumulators, the pumped storage of water shows greater flexibility and is more economical per unit of stored energy, although the efficiency of conversion is lower than that of other means of storing energy.

The maximum overall efficiency of a pumped storage plant in which each element is designed to do its respective duty in the most efficient manner is approximately 65 per cent, obtained as follows:

| | Per cent efficiency |
|---|---|
| (a) Transmission from thermal plant to low tension bus of hydro plant | 96 |
| (b) Driving motor at unity power factor | 97 |
| (c) Average pump efficiency | 85 |
| (d) Slope of pond, head loss through racks etc., when pumping | 98 |
| (e) Slope of pond, head loss through racks etc., when generating | 99 |
| (f) Turbine | 90 |
| (g) Generator | 96 |
| (h) Transmission from hydro plant to low tension bus of thermal plants | 96 |
| Product of all efficiencies (a) to (h) | 63.7 |
| Product of all efficiencies (b) to (g) | 69.0 |

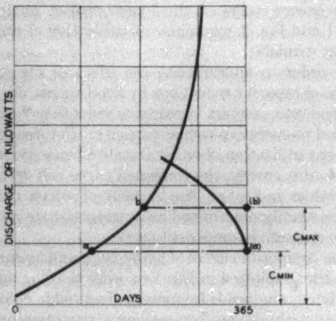

FIG. 4—FLOW DURATION CURVE

Pumping efficiencies of approximately 60 per cent can be obtained by operating in reverse direction, but at the same speed and head, certain types of turbine runners which were originally designed to function only as water wheels.

Substituting in the above tabulation the efficiency of 60 per cent for the high average efficiency of the specially designed pump (85 per cent), the above overall efficiency of conversion of 63.7 per cent is reduced to 45.0 per cent.

As the three-phase generator can be readily adapted for reverse operation as motor merely by the interchange of two armature leads, the dual use of turbine runner and generator as motor-driven pump will entail only a negligible amount of investment to accomplish the purpose of regeneration. If operating conditions are such that the regenerative cycle must normally be repeated every day, the lowering of the overall conversion efficiency will amount to an appreciable sum in an average year, probably sufficient in many instances to overbalance the possible saving in investment.

However, at pondage equipped run-of-river plants, that have a pronounced low-flow stage, corresponding approximately to the flow duration curve shown in Fig. 4, the number of days on which operation under the regenerative cycle is necessary will be relatively small and the loss of efficiency due to the use of the turbine unit as a pump instead of a specially designed pumping unit will not be such an important factor.

Necessity for the regenerative cycle will arise probably only in the event of coincidence of heavy load demands, minimum flow, and outage of steam reserves on the load system served by the hydro plants. The increased energy consumption due to the lowered efficiency need not be viewed therefore as a continual operating expense, but it will be of the utmost importance to establish beyond doubt that the dual use equipment can perform the full duty expected of it for the purpose of firming a certain amount of installed hydro capacity. This phase of the problem is dealt with in Section II. The purpose of the present investigation is to determine for a typical example the approximate amount of additional hydro capacity that may be installed at low increment cost in excess of that capacity which is rendered firm on the system load by the minimum natural inflow.

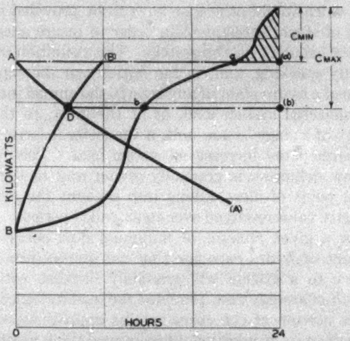

FIG. 5—LOAD DURATION CURVE

The load duration curve for a typical heavy day in Fig. 5 is assumed to be normally supplied by a combined hydro-steam system of which hydro furnishes at times of minimum regulated river flow the cross-hatched upper portion of the load area. C min. represents the corresponding amount of hydro capacity rendering firm peak service to this load system. The area to the left of the curve will be called the no-load area.

The integrated load area below the horizontal line $a(a)$ is plotted at a suitable scale as a curve starting at point $A$ in such a manner that the abscissa of any point along the curve $A(A)$ represents the load area lying above a horizontal line through that point and below line $a(a)$. From point $B$, which corresponds to the minimum load of the load duration curve we plot now a curve *B*(*B*), any abscissa of which represents the integration of the no-load area below a horizontal line through the selected point multiplied by the overall efficiency of conversion. A horizontal line drawn through the point of intersection *D* of these two curves will divide the load curve into an upper area that can be supplied by hydro produced by natural inflow as well as by regenerative cycle, and into a lower area in which the steam plants will operate at 100 per cent load factor.

The assumption has been made in the above that the regenerative cycle is not limited by the capacity of the upper or lower pond or by excessive variations in operating head. It is also apparent that the installed hydro capacity is approximately equal to the full amount of off-peak steam capacity available. A somewhat larger amount of hydro capacity may be installed and render firm peak service if the load system is interconnected with other steam plants that have a large amount of off-peak steam energy available during the pumping hours.

Increasing the installed capacity from C min. to C max. will yield a certain amount of additional high-flow energy as indicated by the area *a*(*a*) (*b*)*b* in Fig. 4. It will be of interest to compare this gain in high-flow energy in an average year with the energy consumed as conversion loss in the regenerative cycle. Instead of integrating the load areas lying between two capacity lines, we can more conveniently compare the increment gain in output per kilowatt for any value of installed capacity with the increment loss corresponding to that capacity. The horizontal distance of the duration curve in Fig. 4 from the 365 day ordinate gives the number of days on which a certain amount of capacity will still be able to turn out full output for 24 hours. Thus the number of days represented by the horizontal intercept to the right of the curve, multiplied by 24 hours will give the energy yield per kilowatt at that value of installed capacity. An incremental loss curve will now be added in which horizontal intercepts also express the energy loss per kilowatt at various values of installed capacity.

The energy consumed for conversion losses is zero at the point C min. and is plotted on the 365 day ordinate. The increment conversion losses of a single day corresponding to an installed and firmed capacity of C max. will be equal to the distance (*b*)*b* indicated in the load duration curve of Fig. 5, multiplied by the coefficient $\frac{(1.0\text{—conv. eff.})}{\text{conv. eff.}}$. The number of days on which such increment conversion loss is incurred can be determined from the flow duration curve of Fig. 4 by converting the whole load area supplied in Fig. 5 by the hydro capacity C max. into 24-hour load at 100 per cent load factor, entering this average load on the duration curve in Fig. 4 and reading the number of days of deficiency at that point. This number of deficiency days is computed to the same scale as the duration curve by multiplying by the incremental loss divided by 24 and is plotted to the left from the 365 day ordinate. The point of intersection of the flow duration curve with the incremental loss curve will indicate the amount of capacity installation beyond which the high-flow energy gains will be exceeded by the conversion losses in an average river year, assuming, of course, that during the entire period of low-flow, firm peak service to the extent of installed hydro capacity must be produced by the combined effect of natural inflow and regenerative cycle and without any assistance whatever from steam reserves.

## SECTION II

One of the best known examples of converting pressure into velocity and back again into pressure is the Venturi meter. Its overall efficiency of conversion is very high. Care is taken in the design so that the flowing water is accelerated and retarded with an almost negligible loss of energy. Such ideal conditions can, of course, not be duplicated in a water wheel with its serial arrangement of stationary and rotating water passages involving sharp changes in velocity and direction of flow. Under those conditions efficiencies in excess of 90 per cent are quite an achievement. A high rate of acceleration is possible without disturbing the continuity of flow which permits a compact design, short water passages, and a minimum of wetted surface and friction. Retardation of water, *i. e.*, conversion of velocity into head, cannot be accomplished at as high a rate as acceleration without disturbing continuity of flow, which causes turbulence and shock losses. Energy conversion in a centrifugal pump, therefore, cannot be carried out at as high a rate of efficiency as in the turbine, because water passages must be designed for a more gradual rate of diffusion, which will require a

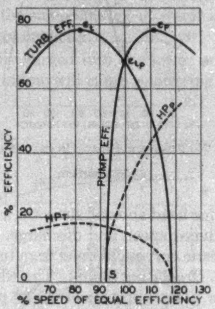

FIG. 6—TURBINE PUMP CHARACTERISTICS

Single-phase centrifugal pump

larger amount of wetted surface and greater friction loss. The best efficiencies ever reached by centrifugal pumps are between 85 and 89 per cent. Although apparently only 5 per cent less than best turbine efficiencies, yet, this difference in terms of losses means that the best pump has from 50 to 75 per cent greater losses than the best turbine.

A centrifugal pump that has its best efficiency under certain conditions of head, speed and discharge for which it is designed, can be made to function as a turbine at the same head and will show the same efficiency, though at reduced speed and discharge. Fig. 6 shows the characteristic curves obtained from tests on a single, stage, 125-hp. circulating pump. The efficiency curves intersect at a point approximately 10 per cent below that of best efficiency. For an installation where the hours of pumping and of generation are approximately equal, synchronous speed of normal operation for this type of runner should be in the vicinity of this point of intersection. There is a certain risk, however, in lowering the operating speed materially below that at which the runner has best pump efficiency, because with only a few per cent further reduction in speed, (or an equivalent increase in head), the efficiency will drop off rapidly and the runner will stop pumping altogether. In the example shown in Fig. 6, this latter point, usually called "speed of impending delivery," lies only about 7 per cent below the speed of equal efficiency.

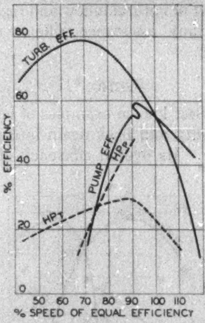

FIG. 7—TURBINE PUMP CHARACTERISTICS

Francis turbine

Another drawback of employing this type of runner for dual use is indicated by the relation of horsepower input for pumping to horsepower output for generation. At best, a runner of the characteristics as found in Fig. 6 may be considered for dual use operation only under certain special conditions where the hours of pumping under average conditions will greatly exceed the hours of generation. For example, at some of the existing seasonal pumped storage plants, a motor pump set may be used as a generator at from 25 to 50 per cent of its rated motor input, and at an efficiency of around 50 per cent on some rare occasions of sharp seasonal peaks of short duration. It will contribute whatever turbine output it is capable of, as so much additional firm peak capacity to the system at practically no additional cost.

That the modern type Francis runner with its short and sharply reduced and warped water passages is not well suited for regenerative operation, is illustrated in the characteristic curves of such a runner shown in Fig. 7. While the maximum efficiency of this turbine runner appears no higher than that of the centrifugal pump shown in Fig. 6, it should be borne in mind that Fig. 7 gives the test results on a small model, whereas the values of Fig. 6 were obtained from a full size installation. Normal synchronous speed of a modern high-specific-speed Francis runner lies usually in a range somewhat below the speed of impending delivery when operating the same runner as a pump against the same head. Except in some rare cases, where an abnormally large overlap of head between serial plants on the same river permits large fluctuations in operating head, or at storage reservoirs having an unusually large drawdown, this type of runner cannot be employed for pumping at synchronous speed. However, if coupled with either dual or variable-speed generators, the modern Francis runner has some distinct possibilities for regeneration.

The tests on this type of runner covered a wide range of conditions as to speed, head, gate opening, etc., in combination with three types of draft tubes; elbow, spiral and straight conical. Some of these test results are shown in Figs. 8 and 9. There was a considerable spread in the speed of impending delivery, as well as in the speed of best pump efficiency for the different types of draft tubes. With the elbow tube, the runner commences to pump at a much lower speed than with the conical tube. The maximum pumping efficiency with the elbow tube was several per cent lower than with the other types of tubes, but at a lower range of speed. Reduced gate openings have the effect of materially lowering the speed of impending delivery for all types of draft tubes.

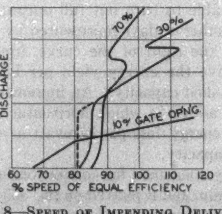

FIG. 8—SPEED OF IMPENDING DELIVERY

Various gate openings—Francis turbine

There is some reasonable expectation that the Francis type of runner can eventually be developed for dual use at synchronous speed, especially at medium head installations, if certain modifications are made in the design, without appreciably increasing the cost of equipment or lowering the turbine efficiency. One of these requirements is that peripheral velocity be raised slightly above the $\sqrt{2gh}$ value corresponding to the highest expected pumping head; changes in cross-sectional area of water passages have to be more gradual, the design then leaning towards a fewer number of, but longer blades; such runners will probably be designed for lower specific speed, the ratio of axial length to diameter more nearly approaching that of the older type of Francis runners.

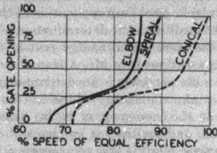

Fig. 9—Speed of Impending Delivery

Different draft tubes—Francis turbine

Among the various types of turbine and pump rotors which are now available and which are designed primarily for a single function, *i. e.*, either generation or pumping, the propeller turbine, and especially the Kaplan adjustable blade type, seem to offer the greatest flexibility for dual use in the regenerative cycle.

Fig. 9 shows the efficiency curves of a 16-inch model over a range of 60 to 130 per cent of rated turbine head. Over this whole range of operation, the efficiency of the model drops only slightly below 60 per cent, the maximum being 65 per cent. The test results were obtained in the low-head laboratory. Although these efficiencies checked very closely with the test results in the high-head laboratory, certain practical limitations were set by cavitation. At operating heads below 50 feet this will probably not be a serious drawback, especially if serial plants on the same river are laid out with a substantial overlap of head.

## Section III

Certain features influencing the extent to which hydro regeneration will be economic have been referred to in the preceding sections as follows:

Relation of deficiencies in flow to duration of high-flow stages.

Amount of pumping power and number of pumping hours during each cycle.

Efficiency of regenerative conversion.

Overlap of head and cavitation limit.

Relation of increment cost of additional hydro capacity including transmission and tie-in investment, to increment cost of steam capacity.

Aside from the above considerations, any one of which may control the upper limit at which regeneration ceases to be profitable, there is one additional factor that will in many instances set a definite limit on the regenerative cycle, namely, the amount of pondage available.

The ideal condition would be the presence of two large lakes, which contain in the first foot or so of storage such a large volume that many times the minimum natural inflow can be shifted every day from the upper to the lower level and back again without any appreciable drawdown in the upper, or rise in the lower level. This ideal condition would be rarely encountered, and usually there will be an inequality in the two ponds, the smaller one of which will of course establish the limit for the regenerative cycle. As this question of pond limitation is of some importance, an approximate formula will be developed for the purpose of establishing a relationship of the energy obtainable by pondage under drawdown conditions to the theoretical energy obtainable by the same amount of water if both ponds were of unlimited capacity.

The water discharged into the lower pond in excess of the natural inflow will cause a lowering of the water level in the upper pond and a rise in the lower pond. The drop in the upper plus the rise in the lower pond represents the reduction in head, under which the upper plant will operate at the end of the drawdown period. The lower plant will operate during the whole drawdown period at a gradually increasing head, the maximum at the end of the drawdown period being equal to normal operating head plus the maximum rise in the lower pond. Thus, there will be on the average a lowering in the combined effective operating head of the two plants, *i. e.*, a reduction in output from natural inflow

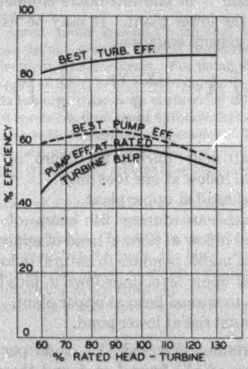

Fig. 10—Turbine Pump Characteristics

Adjustable blade propeller turbine (Kaplan) alone, below that obtainable from the same water under normal head conditions.

Assuming that there will be no physical limitations, other than those controlled by practical operating conditions, along the shores of the lower pool (railroads, highways, buildings, etc.), or at the power house structure itself, we may expect that the excess drawdown may be carried to a point, where either an excessive lowering of head renders turbine operation at the upper plant too inefficient or impractical or where the increased capacity at the lower plant would overload the generators. The limit will probably be first reached at the upper plant and approximately at that head which is the capacity controlling one at times of very high flood stages.

This maximum reduction of head has been assumed at approximately 40 per cent. Instead of expressing pondage, useful for regeneration, in absolute terms of million cubic feet or in cubic feet per second average flow during 24 hours, it will be expressed in relation to minimum natural inflow, calling the ratio between the two $(X)$, which ratio will be shown to have a bearing on the net gain of energy that can be secured over a wide range of pond ratios, *i. e.*, relation of upper pond area to lower pond area.

This net gain $N$ in kilowatt-hours is independent of the head at the lower plant. It may be expressed in the following general equation:

$$N = f_n h_1 \left[ (X) - \frac{(X)(Y)}{2} - \frac{(Y)}{2} \right] + f_n \frac{d_2}{2}$$

in which:

$f_n$ = kilowatt-hour during 24 hours of minimum natural inflow at one foot head.

$h_1$ = normal head at upper plant.

$f_n h_1$ = kilowatt-hour during 24 hours of minimum natural inflow at normal head of upper plant.

$(X)$ = ratio of usable pondage to natural inflow.

$(Y)$ = ratio of upper level drawdown $d_1$ plus lower level rise $d_2$ to normal head at upper plant.

$d_2$ = maximum rise at lower pond.

For a maximum practical $(Y)$ of 40 per cent and different ratios of $(X)$ from 1 to 5 and three assumed pond ratios (unlimited upper pond, both ponds of same characteristics, lower pond unlimited), this equation will lead to the following coefficients of net gain, *i. e.*, relation of kilowatt-hour obtainable by pondage under drawdown conditions to kilowatt-hour obtainable by the same amount of water if both ponds were of unlimited capacity:

| (X) = | 1 | 2 | 5 |
|---|---|---|---|
| | Per cent | Per cent | Per cent |
| Unlimited upper pond | 80 | 80 | 80 |
| Upper and lower pond identical | 70 | 75 | 78 |
| Unlimited lower pond | 60 | 70 | 76 |

## Discussion

**Alex. E. Bauhan:** It is refreshing to see a paper treating the relative economies of water and steam power in such a thoroughly sound manner. It is quite a contrast with some misleading presentations which have been made in the past in which the comparison is made in mills per kwhr, perhaps with some qualifying discussion as to load factor. As in the case of many other problems, comparison of the total annual costs of one plan and of the other must be made before sound conclusions can be drawn.

There are two thoughts presented here, neither of which is a criticism of the paper and both of which I appreciate Mr. Allner is cognizant of, and which he probably felt were beyond the scope of his paper. However, the writer thinks they are worthy of at least mention in order to avoid misapplication of the paper.

The first thought deals with the determination of energy value. This is taken as the incremental energy cost in the competing steam plant and is mentioned by Mr. Allner as averaging about two and one-half mills per kwhr. In determining this value it is not sufficient to take the energy which will be generated by the hydro plant, or the increment of hydro capacity which is under consideration, and multiply it by two and one-half mills. If the competing steam plant is able to generate a larger amount of energy than the hydro capacity, and this is usually the case, especially if one of the later increments of hydro capacity is being considered, this additional energy redounds to the credit of the steam plant to the extent that its incremental cost is less than the incremental cost in the existing steam plants which otherwise would have generated this energy. For instance, consider an increment of firm hydro capacity of one kilowatt which is usable 3,000 hours per year. The use of the competing one-kilowatt of steam plant capacity is perhaps 7,000 hours per year. The excess is 4,000 kwhr, and would be used to relieve generation on older higher cost marginal stations to that extent. If the saving in production expense resulting therefrom is one mill per kwhr, the steam plant receives a credit of $4.00 per kw-year, which of course correspondingly diminishes the value of the hydro installation.

The other thought is that although curves plotted on the basis of per cent capacity installed, such as used in this paper, may show a hydro cost, after the initial development, materially below the hydro value, one must not draw the conclusion that the project is economically justified. The dimension of time enters. One must go a step further and plot hydro costs and hydro value against years. Such a comparison may show that the initial hydro development, especially if it is large in comparison with the annual load growth, has a value less than its cost for a number of years. This loss accumulates with compound interest and unless the profits from future years' operations are marked, it may never be made up. In other words, the project is not economically justified.

The introduction of the time element brings with it the uncertainties of future loads and future competitive plant costs. These uncertainties make the ultimate decision largely a matter of judgment in which, it may be said, the economic analysis is an indispensable aid.

**William McClellan:** Those who, like the writer, have been examining eastern water powers for a great many years will know the progress that has been made and what a vast difference there is in the economic use of water power by and large in the eastern part of the United States where the heads are low compared with the water powers in the mountainous regions in the West. At the beginning we knew no better than to treat these water powers as entities in themselves and we were confronted in most cases with low heads and greatly varying flows. The problem was difficult because the head was not only very variable owing to low water, but also at flood times. Equipment such as discussed in the paper had not yet been designed. A project was regarded as a prime source of power with or without a certain measure of steam reserve. Our only superficial measure of its value was the price per horsepower required for the total development. Later transmission came by which we were enabled, not only to put the power into more distant markets, but also to make the power a part of existing large systems which could be regarded either as sinks for all the kilowatt hours we could develop or, as Mr. Allner has pointed out, some of the powers could be used as power storage devices for lifting off peaks in steam systems and other purposes.

Mr. Allner's paper brings out that a proper point of view is the *sine qua non* in approaching any problem of this sort which has any economic complexity. In brief, this proper point of view is not that of the water power as an entity in itself, but as one of the features in the power supply for a given district or region. When the problem is approached from this standpoint, as has been pointed out, we have the possibility of developing an installed capacity far beyond anything we would have dreamed of in past years. True, it becomes a very nice point for decision, based upon extremely careful analysis, as to just where the stopping point is. Moreover, inasmuch as a large part of the investment in any water proposition is in the base works, including the dam, forebays and tailrace, it becomes a relatively simple matter to prepare for and add successive units as they are economically needed and the business is developed.

The writer had a very interesting experience recently in going through a rather protracted discussion leading up to the introduction of Safe Harbor power into the City of Washington. A few years ago this would have been thought to be impossible because the only consideration then would have been the relatively low average cost of steam power and the relatively high cost of hydraulic power based on average river flow with limited capacities installed. When the engineers, however, presented their figures showing how the one power could be fitted into the other, the possible results were remarkable. It may be said also that some of these developments that have been made and those that will be made in the future are also made possible by a proper point of view in regard to the market. Not only does the modern engineer and power economist fit his sources of power very carefully together so as to get the greatest possible economic production, but an equally careful examination is made of the possible use of this power, the diversity of the various markets in reach, etc. Contracts can therefore be made at varying rates so that every customer is benefited and the company is better off.

**R. E. B. Sharp:** Under section II of the Appendix, Mr. Allner discusses the performance obtained by the dual operation of pumps and turbines. He states "a centrifugal pump that has its best efficiency under certain conditions of head, speed and discharge, for which it is designed, can be made to function as a turbine at the same head and would show the same efficiency though at reduced speed and discharge." This is equivalent to saying that for a given uniform efficiency for both conditions of operation the turbine losses and the pump losses will bear a given relation to each other. These losses, of course, will not be equal, with equal efficiency. It is true that in some cases the turbine and pump efficiencies are the same, as in Fig. 6, but this is not necessarily true for any centrifugal pump.

If the pump losses could be kept as low as the turbine losses, the pump efficiency would be higher than the turbine efficiency. The fact that pump efficiencies are generally lower than turbine efficiencies is evidence of the greater difficulty in keeping pump losses anywhere near as low as turbine losses.

Consider a design of pump where the runner contains vanes, which are long, and which have a small angle with the tangential at discharge (when operating as a pump). The diffusion losses through the runner would probably be relatively low with such a design, resulting in what is considered high pump efficiency, provided other parts are properly designed. When this runner is operated as a turbine, on the other hand, the efficiency might be good, as the long vane passages would result in effective guidance of the water, with friction losses negligible (where the specific speed is low). This design of pump, as a consequence, would show relatively high efficiency, as a pump, and also high efficiency as a turbine.

Consider another design of centrifugal pump provided with shorter length of vanes with a greater angle between these vanes at discharge (when operating as a pump) and the tangential. When operating as a pump the losses due to diffusion, caused by too great an angle between the vanes, and consequently too great a rate of area expansion, would result in relatively low efficiency as a pump. On the other hand, the steep vane angle and short passages would tend to give relatively high efficiency as a turbine.

In view of the above, the writer submits that there is no basis for the efficiency of any centrifugal pump necessarily being the same when operating as a pump as when operating as a turbine.

The I. P. Morris organization has developed a reversible pump-turbine for dual speed operation from a model having a runner 18 in. in diameter at the vane tips. The efficiency as a turbine, as obtained from test, was found to be 89.3 per cent and as a pump, 85.5 per cent. This model was designed to have both the turbine losses and the pump losses as small as practicable. It was realized that it would be more difficult to keep the pump losses small, than the turbine losses, and the runner was designed, to a large extent, to suit pump operation with the vanes fairly long and with an effort to keep the diffusion losses for pump operation low. Nevertheless, in accordance with the test, the pump losses proved to be 59 per cent greater than the turbine losses, as may be deduced from the efficiencies obtained.

A second model runner was tested, having the vanes at the tips more nearly radial. The test showed that efficiency, as a turbine, equaled 87.5 per cent and as a pump 80 per cent. In this case the pump losses proved to be 100 per cent greater than the turbine losses.

The dual speed motor generators required with reversible pump-turbines do not present difficult problems, according to one of the electrical manufacturers. For pump storage projects involving upward of 150-ft head, permitting the use of low specific speed Francis runners, there is no engineering obstacle preventing the use of reversible dual speed hydroelectric units with high efficiency under both conditions of operation. To obtain with such units the best pump efficiency, the amount of power input, when pumping, is materially greater than the power output when generating.

The operation of a pump-turbine at a single speed for reasonable economy, requires that both turbine and pump efficiency be as high as practicable. In addition to raising the efficiency-speed curves throughout the range, the higher the efficiency the closer together are the speeds at which maximum turbine efficiency and maximum pump efficiency occur. That is, as Mr. Lewis F. Moody has pointed out, on the basis of uniform head, $\frac{RPM_T}{RPM_P} = \sqrt{\text{Effic.}_T \times \text{Effic.}_P}$. The pumping operation, however, will necessarily be, to a great extent, against a higher head than when generating, with the consequent additional separation of the two speeds and reduction of efficiency at the common speed. Where, as generally would be the case, the turbine efficiency is decidedly higher than the pumping efficiency, the intersection of these curves, that is the common speed, would occur close to the maximum pumping efficiency. Therefore, the use of a single speed would result in securing almost the maximum pumping efficiency available, with the greater sacrifice in turbine efficiency.

**James E. Stewart:** The writer considers that Mr. Allner's paper very clearly brings out the modern conception that the main value of the utility hydro plant is capacity where there is not a high minimum stream flow.

Unless the flow at hydro stations is backed by natural storage or relatively low cost artificial storage, energy costs for hydro plants cannot usually compete with energy from the modern steam station. In general this statement leaves the steam stations as the cheapest energy makers for most of the population of the United States. The exceptions are where cheap storage is available in lakes, glaciers, snow fields, lava beds, etc. These areas in general are limited to mountainous or glacial regions. In Canada over 95 per cent of the utility load is carried by water power because the high low water flow makes hydro power cheaper per kilowatt hour than steam. In this connection it is to be remembered that practically all Canadian water power developments are in glaciated areas and in addition many are in mountainous territory. There are regions in the United States, particularly in the Rocky and Cascade Mountains and to a lesser extent in the high rain-fall regions of the Appalachian Mountains where water power can compete with steam on an energy basis alone. Elsewhere with rare exceptions it is only on a capacity basis, or energy and capacity basis that water power works out more economically than steam, and then in general the best economy has proved to be a combination of steam and water power.

**Ireal A. Winter:** The part of the paper dealing with hydro-regeneration equipment is of especial interest. This is a pioneer work in the States and shows in a concrete way what can be expected by further research along this line. It is the writer's opinion that the use of hydro-power has a most important part to play in the economics of interconnected power systems in the future. The subject matter discussed in the paper points the way to a new line of thinking for the hydroelectric interests of the country. The time is fast approaching when the conception of a wide use hydro-regeneration will mature into a concrete fact. Further specific evidence of what the field offers, such as brought out in the paper, will do much to accelerate the development and installation of suitable equipment to the economic advantage of the electrical industry.

# Safe Harbor Project

BY N. B. HIGGINS*

Member, A.I.E.E.

***Synopsis.**—The Safe Harbor Water Power Corporation has recently completed the dam and initial section of the power house to develop the fall of the Susquehanna river between the Holtwood project backwater and Columbia, Pennsylvania. This development, when completed, will be one of the largest hydroelectric developments in the United States.*

*In the initial project there will be installed 255,000 turbine horsepower, and in the completed project 510,000 turbine horsepower. One of the most notable features is the 42,500-hp. Kaplan turbines, the most powerful ever built and the largest in physical dimensions so far installed on this continent.*

*In the average year, with full utilization, the initial project will generate over 800,000,000 kw-hr. for distribution through the transmission system of the Pennsylvania Water and Power Company to Baltimore, Maryland, and Pennsylvania customers. Transmission to Baltimore will be at 230 kv. and to Pennsylvania customers at 69 kv. and 132 kv.*

*The power house and dam have a combined length of 5,000 ft.; the length of the dam is 4,084 ft., and the ultimate length of the power house is 916 ft. The spillway length is 1,810 ft.; the spillway is equipped for its entire length with crest gates, of which there are thirty-two 48 ft. long and 35 ft. high. The discharge capacity of the spillway at normal elevation 225.0, is 970,000 c.f.s., and at forebay elevation 227.0 (ultimate) 1,150,000 c.f.s.*

*The lake created by the dam impounds a useful storage of 3 billion cu. ft., and has the following dimensions: length 10 mi., width 0.4 mi. to 2.0 mi.; area 10.5 sq. mi.*

*On the east side of the river, 8.5 mi. of the Columbia & Port Deposit Branch of The Pennsylvania Railroad were raised a maximum of 8 ft.*

*The delivery of power to Baltimore was started 1 year, 8 months, and 7 days after work was started on the project site, an outstanding achievement in the annals of hydroelectric projects of this magnitude.*

* * * * *

## INTRODUCTION

THE lower Susquehanna basin between Columbia, Pa. and the Chesapeake bay, attracted the attention of waterpower promoters early in the history of hydroelectric development. Between these points there is a difference in elevation of about 227.0 ft. Several schemes were projected by rival promoters and engineers. Finally a merger of certain interests led to the formation of the McCall Ferry Power Company, which began work near McCall Ferry, Pa. This company failed in 1907 and was succeeded by the Pennsylvania Water and Power Company.

The initial development, now known as the Holtwood project, went into operation in 1910. This left undeveloped and available a fall of about 100 ft. below, and 57 ft. above Holtwood. Of these possible developments, the lower (Conowingo project) was constructed and went into operation in 1928.

The Safe Harbor Water Power Corporation was formed by the Aldred interests, who also own and operate the Pennsylvania Water and Power Company's Holtwood project, eight miles downstream from Safe Harbor. These properties, together with the steam stations of the Consolidated Gas Electric Light and Power Company in Baltimore, are interconnected and form a unified system operated for the best overall economy throughout.

## OUTLINE OF PROJECT

The development of the fall between the Holtwood pool and Columbia by the Safe Harbor Water Power Corp., is the subject of this paper. The site of the project is about 1,100 ft. upstream from the mouth of Conestoga creek. This development, when completed, will have an installed capacity of 510,000 hp., in twelve Kaplan turbines, each of 42,500 hp. capacity, operating at a speed of 109.1 r.p.m. under a head of 55 ft. Ten of these turbines will drive 36,000-kva., 60-cycle, three-phase, 80 per cent—100 per cent power factor, 13,800-volt generators, and two will drive 37,500-kva., 25-cycle, single-phase, 80 per cent power factor, 13,300-volt generators. There are also included in the ultimate plan, four 25 cycle/60 cycle frequency changers of the outdoor type; the generating end will be rated at 31,250 kva., 80 per cent power factor, 300 r.p.m., 13,300 volts.

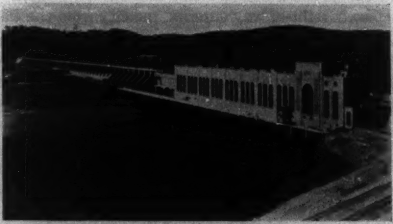

FIG. 1—GENERAL VIEW OF THE SAFE HARBOR PROJECT

The initial step of the development includes five 60-cycle units and one 25-cycle unit, and one frequency changer; four 60-cycle units are now in operation, and it is expected that another 60-cycle unit, one 25-cycle unit, and a frequency changer will be installed before the end of 1933.

A major problem in electrical design at Safe Harbor has been to produce a flexible layout, which will permit the installation as required of equipment for generating, transforming, and transmitting 60 cycle, three-phase, and 25 cycle, single-phase. All generating equipment and the 60-cycle low-tension bus are located in the power house. All 60-cycle transformers are of the outdoor type, and located adjacent to the power house.

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

The combined 69-kv. and 230-kv., 60-cycle substation will ultimately be located on the top of the hill, directly east of the power house. The frequency changers, the 25-cycle low-tension bus, and the 132-kv., 25-cycle step-up substation will be located east of the power house.

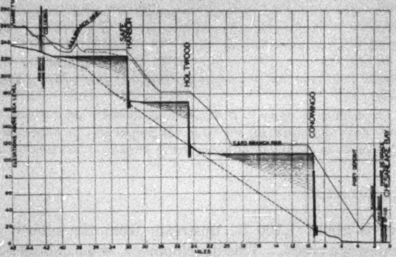


Fig. 2—Profile of the Susquehanna River from Columbia, Pa. to Chesapeake Bay

One 230-kv. circuit has been constructed between Safe Harbor and the Westport station of the Consolidated Gas Electric Light and Power Company in Baltimore, Maryland. Another 230-kv. circuit will be constructed to Baltimore within the next few years, over a separate right-of-way entering the city from the east.

A 69-kv. double-circuit transmission line, about one mile in length, has been constructed to tie Safe Harbor into the existing 69-kv. system of the Pennsylvania Water and Power Company. This connection is made to the Holtwood circuits at a new switching station at Lehman Farm.

The power house is in line with, and forms a continuation of the dam. The substructure is of reinforced concrete, and the superstructure of brick and tile.

The total combined length of the concrete dam and power house is 5,000 ft., made up as follows: power house, 916 ft.; bulkhead and abutments, 2,274 ft.; spillway, of the ogee type, 1,810 ft. The entire spillway is equipped with crest gates. Although the highest flood of record is estimated to have been 725,000 c.f.s., the spillway was dimensioned for a maximum discharge of 970,000 c.f.s. at forebay elevation 225.0, and 1,150,000 c.f.s. at forebay elevation 227.0.

The forebay is enclosed by a skimmer wall and dyke to prevent the entry of trash and ice.

Fig. 3 shows the general arrangement plan of structures.

A general description of the project, with particular attention to the principal features, follows:

## The Susquehanna River

In extent of drainage basin, and in total and average runoff, the Susquehanna river is the largest river flowing into the North Atlantic ocean, with the exception of the St. Lawrence. Its watershed includes 27,400 sq. mi. in the states of New York, Pennsylvania, and Maryland. Yet, in spite of this vast tributary area, the stream itself is of little use in commerce. One of the principal reasons for this is the unique fact that the steep slopes in the course of the river occur in the lower reaches, where the stream has cut its way through the Piedmont plateau. Tidewater from Chesapeake bay extends only five or six miles up the river and there is practically no navigation above the tidewater limit.

From Columbia to Tidewater, a distance of 39 mi., the river is walled in by steep bluffs or hills, and the main channel varies in width from a few hundred yards to almost two miles. As a result of these conditions there has been no industrial development, other than transportation, in this reach of the river; the tracks of the Columbia and Port Deposit Railroad skirt the eastern shore of the river for the entire distance.

These conditions of rapid descent, steep banks, and the absence of populous towns in a region in close proximity to large industrial centers, made this reach of the river attractive from a power development standpoint.

## Project Site

Many of the flowage rights required were already in the hands of the Pennsylvania Water and Power Company as early as 1910. In the twenty years intervening much additional land had been acquired, so that most of the real estate and flowage rights required for the project had been obtained a number of years before initiating the work.

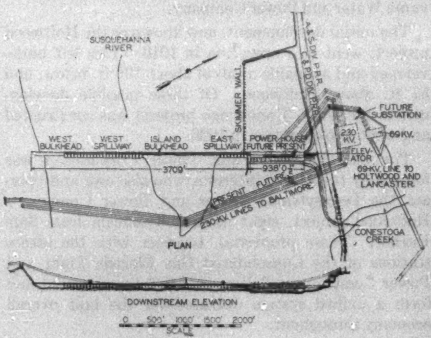


Fig. 3—General Layout of Structures

During this period the engineering staff of the Pennsylvania Water and Power Company made numerous studies of the power possibilities of this project.

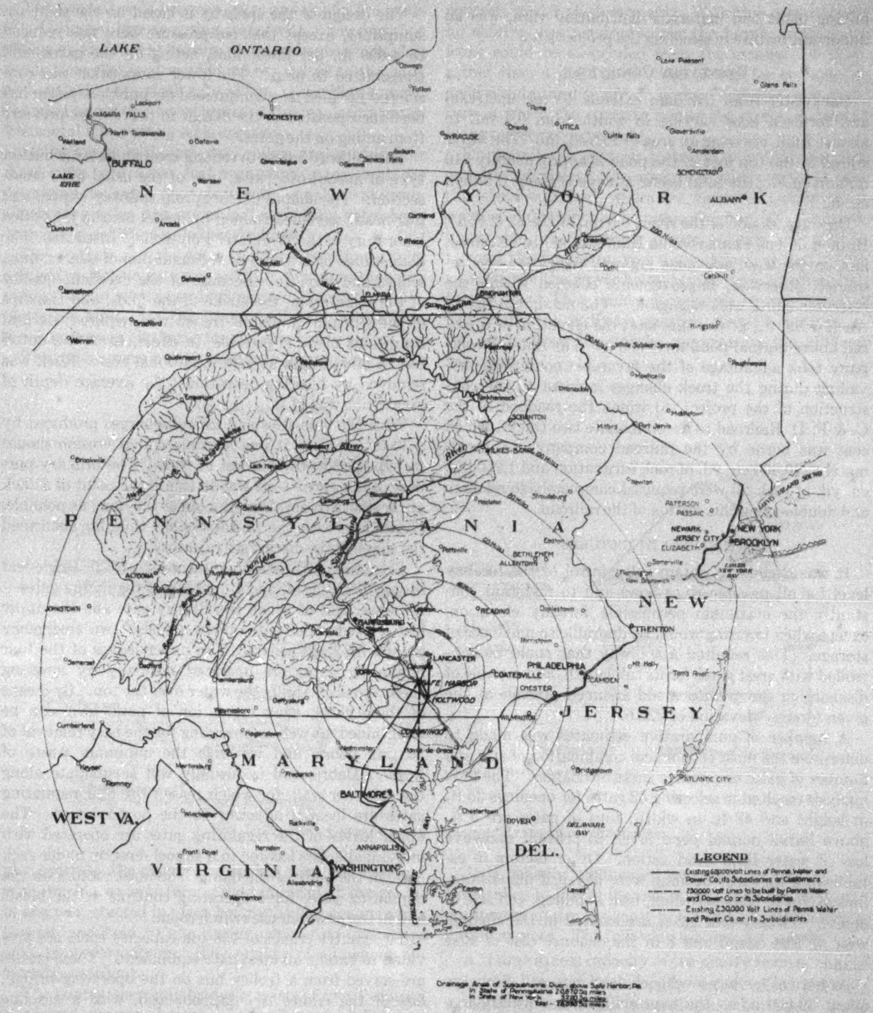

LAKE ONTARIO
NEW YORK
PENNSYLVANIA
NEW JERSEY
MARYLAND
WEST VA.
VIRGINIA
DEL.
LAKE ERIE
BUFFALO
NIAGARA FALLS
ROCHESTER
SYRACUSE
UTICA
SCHENECTADY
ALBANY
SCRANTON
WILKES-BARRE
HARRISBURG
READING
BETHLEHEM
ALLENTOWN
LANCASTER
SAFE HARBOR
HOLTWOOD
CONOWINGO
COATESVILLE
PHILADELPHIA
CAMDEN
CHESTER
WILMINGTON
TRENTON
NEWARK
JERSEY CITY
ELIZABETH
PATERSON
PASSAIC
NEW YORK
BROOKLYN
ATLANTIC CITY
BALTIMORE
ANNAPOLIS
WASHINGTON
ALTOONA
JOHNSTOWN
DOVER
DELAWARE BAY
CHESAPEAKE BAY
LONG ISLAND SOUND
LEGEND
Existing 66,000 volt Lines of Penna Water and Power Co., its Subsidiaries or Customers
230,000 volt Lines to be built by Penna Water and Power Co or its Subsidiaries
Existing 230,000 Volt Lines of Penna Water and Power Co or its Subsidiaries
Drainage Area of Susquehanna River above Safe Harbor, Pa.
In State of Pennsylvania 20,870 sq miles
In State of New York [illegible] sq miles
Total [illegible] sq miles

FIG. 4—MAP OF THE SUSQUEHANNA RIVER DRAINAGE AREA

Several sites were considered within a range of two miles upstream of the mouth of Conestoga creek before the site was finally selected. During 1928 an extensive program of core borings was conducted and foundation conditions were found to be satisfactory for dam construction.

A location for the construction plant and classification yards was an important consideration. Owing to the steep banks and bordering railroads, there was no favorable site along the river. The valley of Conestoga creek, just above the mouth, was found very favorable and used for this purpose. A large island in the middle of the river that could be utilized to advantage for river diversion, as well as being a suitable site for the concrete mixing plant and materials distributing yard, was an important feature in selecting the project site.

### RESERVOIR CONDITIONS

Backwater from the dam extends 10 mi. upstream and forms a lake varying in width from 0.4 mi. to almost 2 mi., covering an area of 10.5 sq. mi. The water stored in the top foot of the pond is approximately 310 million cu. ft.; the total useful storage is about 3 billion cu. ft.

On the east side of the river, 8.5 mi. of the C. & P. D. Branch of The Pennsylvania Railroad had to be raised, and on the west side some highway relocation was required; otherwise, improvements effected within the reservoir limits were negligible. The maximum rise in track is 8.5 ft., at the dam site; the elevation of top of rail above normal pond level is 8 ft. The railroad company took advantage of the favorable conditions prevailing during the track changes incident to the construction of the project, to widen the roadbed of the C. & P. D. Railroad to accommodate two tracks, which cost was borne by the railroad company. Approximately 270,000 cu. yd. of rock excavation and 1,250,000 cu. yd. of rock fill were required completely to relocate and double-track this section of the railroad.

### HYDRAULIC STRUCTURES

It was desired to obtain full control of the forebay level for all possible river flows and to maintain constantly the maximum permissible forebay elevation, except when lowering would be desirable to make use of storage. This required a spillway that could be controlled with crest gates for its full length, and capable of discharging the greatest flood assumed possible at the given forebay elevation of 225.0.

A number of comparative estimates was made to determine the most economical combination of size and number of gates to produce these discharges. The final analysis resulted in selecting 32 gates for openings 35 ft. in height and 48 ft. in width; tops of gates are 5 ft. above initial normal pond level, to prevent excessive loss of water from wind action. Other factors in establishing the clear opening were physical dimensions, limitations in transportation, field handling, and size of debris. Twenty-four gates are located in the channel west of Else island and 8 in the channel east of Else island.

At normal forebay level each flood gate will discharge about 30,000 c.f.s.; the west spillway has a discharge capacity of 720,000 c.f.s., which is equal to the maximum flood of record.

The bulkhead sections are conventional gravity structures, designed for compression over the entire foundation joint for headwater at elevation 228.0, 10,000 lb. per lineal foot of ice pressure at the same elevation and uplift corresponding to full head at the heel, decreasing to tailwater head at the toe following a gradient determined by the foundation drainage system.

The design of the spillway is based on the same assumptions, except that ice pressure here was reduced to 4,000 lb. per lineal foot, acting on the gates, and transmitted to piers. The lower assumption was considered justified as a compressed air bubbler system has been incorporated in the design to prevent ice pressure from acting on the gates.

The spillway has an overhung crest and a large bucket type of apron; otherwise, it is of the usual ogee cross-section. The shapes of the apron, spillway nappe, and pier noses, were determined by model tests in the Alden laboratory of the Worcester Polytechnic Institute. The dam stands on a sound rock foundation of quartz, mica schist, and phyllite. Because of the excellent quality of the foundation, the strike of the folds, and the dips of the stratum, no cutoff trench was required; natural conditions made it possible, in effect, to obtain cutoff trench advantages at little additional cost. Rock was removed by blasting operations; the average depth of excavation was 11 ft.

With the velocities and unit discharges produced by a 30-ft. overflow, it was recognized that erosion should be expected in the hardest of rock. The primary purpose of the apron tests was to locate the point of attack as far downstream, from the toe of the dam, as possible. Experience with the prototype has thus far confirmed the shape of the discharge trajectory.

The crest gate equipment consists of 28 single-leaf Stoney flood gates, and 4 double-leaf regulating gates—the lower leaf of which is a Stoney gate and the upper leaf a fixed roller gate; there are also two emergency gates with fixed rollers. The upper leaves of the four regulating gates are operated normally by lowering them and discharging the water over the top. By means of these gates, close regulation of pond level can be maintained, as well as providing for the easy removal of floating debris and ice with the minimum waste of water. Debris and ice usually will accumulate along the skimmer wall, for which reason the four regulating gates are located adjacent to the power house. The upper leaves of the regulating gates are operated with individual hoists located in a tunnel directly under each gate, in the body of the dam. The hoist motors for the regulating gates have operating controls at the hoists and in the power house switch room.

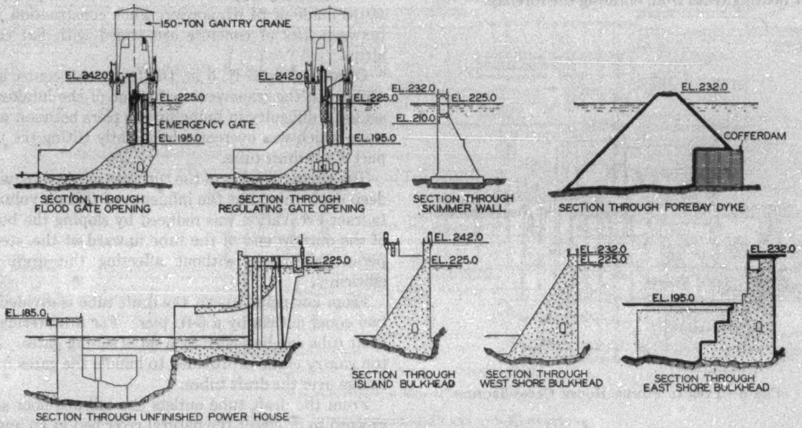
Two gantry cranes of 150-ton capacity each, are provided to handle all crest gate equipment. These cranes are served from a trolley bus on the operating bridge; one of the cranes is equipped, also, with a gasoline engine-generator set for emergency operation. Attachment of gates to the gantries is by means of a lifting beam.

The flood gates are of the usual design of horizontal fabricated girders supporting a skin plate through vertical intermediate beams. The respective weights are 86 tons each for the flood gates (excluding roller trains), and 100 tons each (including fixed wheels) for the emergency gates.

The vertical seals between gates and guides are made of a U-shaped bronze spring plate, with a wearing shoe sliding on an Ascoloy bearing plate welded to the guides; the bottom seal is of molded rubber bolted to the gate, and seats on the steel gate sill in the spillway crest. Between upper and lower leaves of the regulating gates, horizontal brass spring seals are used.

Roller trains with cast steel rollers are provided for flood gates and lower leaf regulating gates, and are connected to gates and piers with equalizer sheaves. Emergency gates and upper leaf regulating gates have bronze-bushed, fixed rolled-steel wheels.

Due to their size, the gates could not be shipped fully assembled, but no gate was split up into more than five pieces. Gates were assembled on two concrete erection platforms built into the island bulkhead, which also serve as storage platforms for the emergency gates.



150-TON GANTRY CRANE
EL. 242.0
EL. 225.0
EMERGENCY GATE
EL. 195.0
SECTION THROUGH FLOOD GATE OPENING
EL. 242.0
EL. 225.0
EL. 195.0
SECTION THROUGH REGULATING GATE OPENING
EL. 232.0
EL. 225.0
EL. 210.0
SECTION THROUGH SKIMMER WALL
EL. 232.0
COFFERDAM
SECTION THROUGH FOREBAY DYKE
EL. 185.0
EL. 225.0
SECTION THROUGH UNFINISHED POWER HOUSE
EL. 242.0
EL. 225.0
SECTION THROUGH ISLAND BULKHEAD
EL. 232.0
EL. 225.0
SECTION THROUGH WEST SHORE BULKHEAD
EL. 232.0
EL. 195.0
SECTION THROUGH EAST SHORE BULKHEAD

Fig. 5—Typical Cross-Section Through Hydraulic Structures

The guides were not grouted into grooves left in the pier concrete, the usual practise, but were tied together with bracing, so as to form a rigid frame of all the guides in one pier, erected in place before the pier concrete was poured, and held to line during concreting operations with temporary struts. The quality of alinement obtained is excellent.

The gantry operating bridge consists of two T-shaped reinforced concrete beams. There is no deck between the beams, so that gates suspended from gantries can travel with their bottom edge below the level of the gantry rails, whereby shorter gantries are used, and a considerable quantity of concrete was saved.

The main reinforcement of the bridge girders consists of a structural steel truss, dimensioned to take dead loads resulting from forms and concrete. For all live loads, the truss steel, supplemented with bars, forms the concrete girder reinforcement. With this construction, no shoring was required under the forms, as all formwork could be suspended from the trusses. A truss, rather than a plate girder, was chosen for economy in dead weight, and to obtain a more homogeneous structure in which the concrete carries the stress, instead of being merely added weight.

To permit the gantries to travel over both the east and west spillways, the operating bridge extends over the island bulkhead, where the upstream gantry rail is supported directly on the mass concrete. On the power house side, the operating bridge extends about 50 ft. beyond the first gate, and the railroad, as well as the craneway of the power house intake deck, overlaps into this space. This makes it possible to run railroad cars under the spillway gantries, as well as to transfer loads from the intake gantries to the spillway gantries.

It is believed that every reasonable precaution has been taken to insure the safe operation of the crest gate equipment under the most unfavorable combination of circumstances. The following features are noted:

a. Large excess capacity of the gantry cranes.

b. One crane can handle gates with sufficient rapidity to meet any normal condition; two cranes are provided.

c. Different sources of power for the gantries.

d. One crane is provided with a gas engine generating set.

e. Equipment to electrically heat the roller tracks and seal plates on the gate guides.

f. A compressed air bubbling system to prevent ice formation on the upstream side of the gates.

### FOREBAY

Experience at Holtwood had demonstrated the value of a fully enclosed forebay when turbine intakes are shallow, and this feature was incorporated into the Safe Harbor design. The forebay is enclosed by a skimmer wall 1,500 ft. long, extending upstream at right angles to the dam, to a junction with a rock-filled dyke about 1,000 ft. in length, extending from the river bank. The skimmer wall intersects the dam at the pier between the first and second regulating gates. A regulating gate discharging from the forebay provides for the disposal of trash that may enter, or ice that may form in the forebay.

The lower edge of the skimmer wall is, at elevation 210.0, 15 ft. below normal water level. Under the full discharge of twelve turbines, the water velocity through the skimmer wall should not exceed 1.75 ft. per second. This velocity is believed to be sufficiently low to prevent floating trash from entering the forebay.

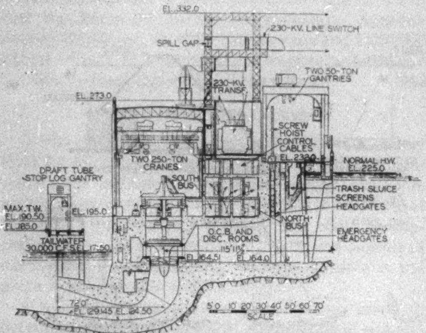


Fig. 6—Typical Power House Cross-Section

The skimmer wall structure is a vertical curtain of concrete, supported on piers 53 ft. on centers. It was designed to withstand an ice pressure of 4,000 lb. per lineal foot from the river side, or 2,000 lb. per lineal foot from the forebay side. With a view to eliminating ice pressure entirely, a compressed air bubbler system is provided, with outlets on both sides of the wall. The top was developed into a walkway 8 ft. wide. The curtain wall, supporting piers, and struts are of structural steel encased in concrete. This type of construction effected a large saving in construction time.

### POWER HOUSE

The site selected for the power house is in the low-water channel of the river near the Lancaster county shore; minimum excavation for power house and tailrace was an important consideration in the selection of this site. Fig. 6, a transverse section, and Fig. 7, sectional plans and elevations through the power house, show the principal features.

The ultimate length of the power house will be 916 ft.; the initial section is 642 ft. long, with space for seven units. A space 506 ft. long is occupied by the four completed and three uncompleted main units, and two service units; 36 ft. by the equipment assembly space, and the 100 ft. at the shore end by filter plant, boiler room, storerooms, repair shop, administrative and engineering offices, and other general utility rooms; the width is 56.04 ft. and the height above operating floor is 78 ft. A railroad connection extends into the generator room assembly bay.

The physical dimensions of the Safe Harbor turbines are the largest for this type of unit so far installed in this country. The maximum scroll case and draft tube width is 55 ft.; the thickness of piers between units is 7 ft., making the unit spacing 62 ft. Below the water line all contraction joints are sealed with crimped sealing strips made of 24 oz. copper, while construction joints between lifts of concrete are sealed with flat copper strips.

Offsetting by 2 ft. 6 in. the transverse center line of units with the transverse centerline of the intakes presented a difficulty in lining up the piers between waterways which was overcome by slightly tilting the upper part of the draft tube.

The characteristics of the turbines selected required a deep draft tube, but the influence of this on volume of tailrace excavation was reduced by sloping the bottom of the outflow end of the tube upward at the steepest permissible angle without affecting the draft tube efficiency.

From low point to exit the draft tube is divided into two equal outlets by a 5-ft. pier. For unwatering, the draft tube can be sealed by a set of sliding gates. A 25-ton gantry crane is provided to handle the gates from a bridge over the draft tubes.

From the draft tube outlets the tailrace floor slopes upward to intersect the natural river bed at an angle of 6 deg. The maximum depth of rock excavation was about 40 ft.; 180,000 cu. yds. of solid rock was excavated to form the tailrace channel. This excavation is the total for the ultimate plant; likewise, the substructure was excavated for all future units. The principal reasons for this procedure at this time are: low cost, elimination of subaqueous excavation in the future, simplification of future power house extension, and a deficiency of rock fill material from required excavation.

The intake portion of the power house substructure for the five future units was completed, excepting that no intake gate hoists or screens were installed. The intake gates for future units were an important part of the scheme for the control and discharge of the river flow during closure of the last cofferdam.

The floors of the intakes are level at approximately the same elevation as the floor of the forebay; each intake consists of three water passages, with smooth sloping bell mouth at the intake. The cross-section of the water passages at the head gates measures 15 ft. 8 in. wide by 29 ft. 4½ in. high. Each water passage is controlled by one intake gate; slots are provided in the head works in front of head gates for the placing of emergency gates when head gates are taken out of service. Velocities through the gross area of the intake cross-sections vary from 3.32 ft. per sec. at entry to 7.25 ft. per sec. at the scroll case intake.

The center gate of each intake travels on fixed rollers, and is operated with a motor-driven screw hoist; the two outside gates are sliding gates, and are handled with a 50-ton intake gantry crane, of which two are provided. The screw-hoist-operated gate can be raised or lowered under full unbalanced water pressure. The sliding gates are designed to be handled under balanced water pressure only. Emergency valves are provided in the sliding gates for filling the intakes in event of screw hoist motor failure.

The omission of hoisting mechanism on two-thirds of all head-gates resulted in a substantial saving in cost, and slows up the starting operation to a negligible degree, as a unit can be started with the center gate alone open.

The emergency gates are similar to, and are handled in the same manner as the sliding headgates.

The seals of the intake gate equipment are of molded rubber and bronze spring plates.

Gate guides were fully erected for the intakes of two units before concrete was poured; the erection procedure was the same as that used on the spillway gates.

A single intake screen is made up into five vertical sections 12 ft. high and 18 ft. wide, and slides in slots similar to the gate slots. The face of the screen has a batter of 1 in 24. Individual screen bars and their supporting frame are designed for an unbalanced head of 15 ft. of water. The vertical screen bars were designed to offer a minimum resistance in the water passages; this developed to be a shape similar to that of an airplane strut. Intermediate horizontal and vertical supports for the screen bars are flat plates with an elliptically shaped leading edge. In addition to reducing the loss of head, a flow free of eddies will decrease the tendency for frazil ice to adhere to the screens. Intake screens are of welded construction throughout.

There is provision for a mechanical trash rake, but the rake will be installed in the layout only if found necessary. Surface trash and ice that may collect at the turbine intakes can be discharged directly over the screens into the trash sluice built into the substructure. The crest elevation of the sluice is one foot below normal forebay level, and is closed off from the forebay by gates, which, when raised, permit the discharge of all floating debris into the sluice, from where it is carried directly to the tailrace. Compressed air can be discharged at points on the periphery of the intakes to dislodge and float waterlogged debris.

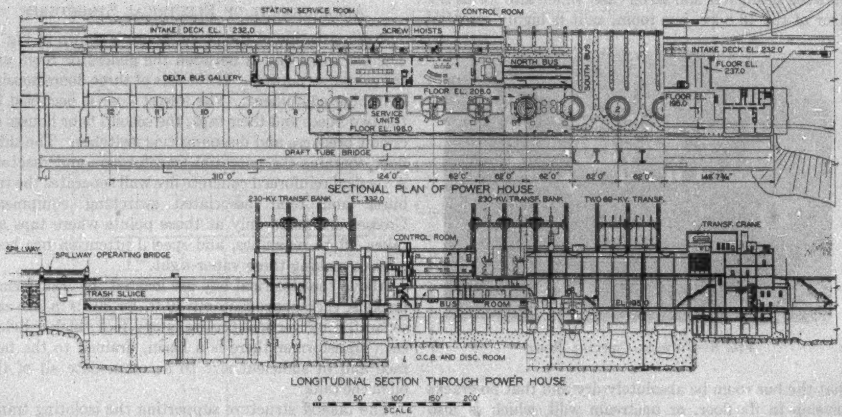

STATION SERVICE ROOM
CONTROL ROOM
INTAKE DECK EL. 232.0
SCREW HOISTS
NORTH BUS
SOUTH BUS
INTAKE DECK EL. 232.0'
FLOOR EL. 237.0
DELTA BUS GALLERY
FLOOR EL. 208.0
SERVICE UNITS
FLOOR EL. 196.0
FLOOR EL. 195.0
12
11
10
9
8
1
2
DRAFT TUBE BRIDGE
310'0"
124'0"
62'0"
62'0"
62'0"
62'0"
62'0"
148'7¾"
SECTIONAL PLAN OF POWER HOUSE
230-KV. TRANSF. BANK
EL. 332.0
230-KV. TRANSF. BANK
TWO 69-KV. TRANSF.
TRANSF. CRANE
CONTROL ROOM
SPILLWAY
SPILLWAY OPERATING BRIDGE
TRASH SLUICE
BUS ROOM
EL. 195.0
O.C.B. AND DISC. ROOM
LONGITUDINAL SECTION THROUGH POWER HOUSE
0
50'
100'
150'
200'
SCALE

Fig. 7—Power House Sectional Plans and Elevations

Electric heating of screens to prevent adherence of frazil ice has been provided for to the extent that conduit has been installed to distribute power for this purpose on the intake deck. A tunnel is provided on the upstream side of the intake deck to house transformers and a screen heating bus. This tunnel serves at the same time as a second skimmer wall to keep the intakes clear of debris.

Another means to reduce or eliminate ice troubles in the intakes is a provision to discharge the air from the exhaust duct tunnel of the power house ventilating systems, into the space over the screens and below the intake deck. The intake deck is covered with floor plates to provide necessary working space, and to eliminate the need of railings. The intake deck is served by a standard gage track, and an 8-ft. gage track for transformer handling.

There is but one main operating floor in the generator room. Consolidating the hydraulic operating equipment simplified the work of attendants, as well as reduced the height of the power house. The choice of umbrella type generators also effected a saving in power house height; however, the concentrated reactions from generator and turbine loads on the concrete of the scroll case, which is, also, highly stressed from water pressure, produced a complicated structural problem. This required the use of high quality, heavily reinforced concrete, in order to insure density and high strength. The same consideration applied to the slab over the intake between headgates and scroll case, which also forms the floor of the 13.8-kv. bus room, as it is highly essential that the bus room be absolutely dry and that no cracks develop in its floor, or upstream wall, which is also exposed to water pressure. As an additional precaution against water seepage, the bus room has a false floor and false upstream wall, with an air space between the latter and the concrete bulkhead, and a gravel fill between floor topping and intake roof slab. Any water that may seep through the upstream wall or floor will be intercepted and discharged to the power house drainage system.

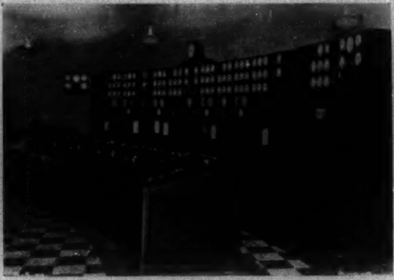


FIG. 8—VIEW IN CONTROL ROOM

The power house superstructure is of steel frame, with buff exterior brick and glazed stippled tile interior curtain walls, and concrete roof. The electrical bay is described under "Electrical Structures."

The water- and oil-proofing of the transformer deck consists of a membrane of 24 oz. copper, which is protected with a three-in. concrete slab. The copper lining extends two feet all around above the floor of the pocket.

For the handling of transformers between the generator room floor where they are unloaded from railroad cars, to the transformer deck, an enclosed transfer bay is provided at the shore end of the building. This structure is elevated above and extends across the generator room. This bay is equipped with a special 250-ton crane operating at right angles to the generator room axis, to hoist and transport transformers between the generator room floor and the intake deck, where they can be placed on a transformer car and transported to their operating positions.

In the solution of this arrangement, it was found necessary to lower the runway of the generator room cranes to the same elevation as the transformer deck. This condition required a special design of short-legged gantry crane for the generator room. Two 250-ton cranes of this type have been installed; each crane carries two 125-ton traveling hoists and two 15-ton auxiliary hoists. These two cranes proved to be important factors in the speed with which machinery was installed.

## ARRANGEMENT OF ELECTRICAL STRUCTURES

A cross-section of the power house is shown in Fig. 6. The electrical bay is between the generator room and the intake structures. It consists of three floors housing switching equipment. The lowest floor is occupied by the two buses and their taps; the second floor houses oil circuit breakers and disconnecting switches. The third floor contains the potential transformers and reactors. A vertical reinforced concrete fire wall separates the two buses and their associated switching equipment. Crosses are made only at those points where taps are taken off to machines, and special attention has been paid to making these vapor-tight.

Above the electrical bay are located the transformer pockets, each approximately 40 ft. by 30 ft. in size and separated by vertical fire walls one foot thick. Below each transformer there is a basin, drained to the tailrace and of sufficient size to accommodate all of the oil in the tank.

The takeoff structure supporting the isolating transformer disconnectors, the lightning arrester disconnectors, and the outgoing spans across the forebay is located directly above the transformers. Safe and quick maintenance on all switching equipment on this structure is made possible by a complete system of access ladders and working platforms.

In the center of the station a space 165 ft. in length above the electrical bay is devoted to the control and terminal rooms, batteries, station service transformers, and station service switchboards.

The control room (Fig. 8) is 83 ft. by 37 ft. and is located on the top floor of the control building. A terminal and conduit room is located below it. The switchboard is made up of three semi-circular boards consisting of a sloping bench, and vertical instrument and relay boards. Along the front and rear walls of the room are located the house service control board and the switchboard for the temporary line relays (which will later be transferred to the substation), the temperature indicators, river control, battery distribution, annunciators, totalizing and other miscellaneous controls.

### 60-CYCLE GENERATING SYSTEM

The four 60-cycle generators now in operation are installed in unit spaces Nos. 3, 4, 5 and 6. Fig. 9 is the main one-line diagram for the installation of these units.

In accordance with present plans, there will be ultimately ten 60-cycle main units occupying positions Nos. 3 to 12, inclusive. The 60-cycle generation is at 13,800 volts, three-phase, and ultimately will feed into a double bus system of eight sections, with four sections per bus. There will be supplied from this bus three 230-kv. step-up transformer banks and three 69-kv. step-up banks. Equipment is connected to the bus by selector oil circuit breakers. Reactors will be installed as needed to hold the short circuit values below 1,500,000 kva.

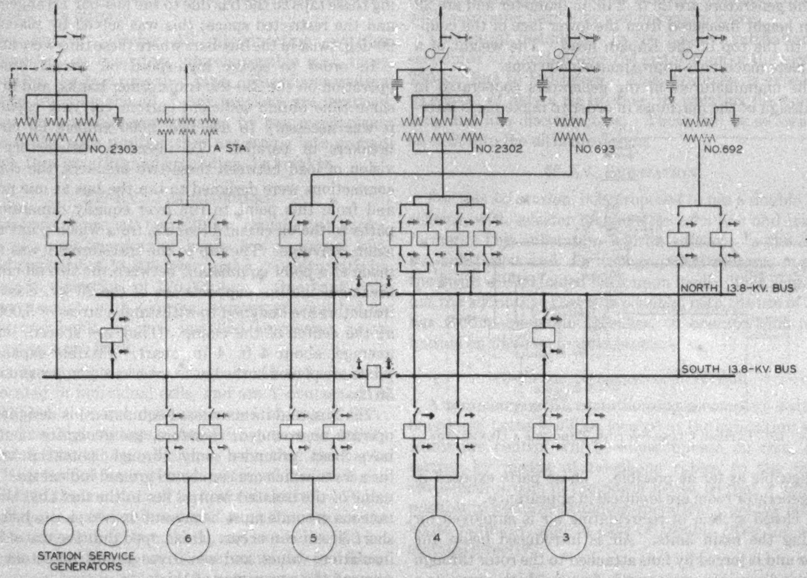


FIG. 9—SINGLE-LINE DIAGRAM, 13.8-KV. MAIN BUS

Only the simplest high voltage switching is provided at the power house. This consists of a motor-driven isolating disconnect with ground switches, for each transformer. The lightning arresters, spill gaps, and the lightning arrester disconnecting switches for protection of the transformers are also located at the power house, one set being connected to the outgoing leads of each transformer.

At the present time there is no high-tension bus, each transformer bank being connected directly to a transmission line. Either or both of the two 230-kv. banks can be tied to the single 230-kv. Baltimore circuit.

In the preliminary designs of the station, comparative studies were made of several layouts; however, the probable use of frequency changers for railway supply, the necessity for the use of two transmission voltages, considerations of existing system operating connections, and the reduction of early investment in costly high-voltage switching equipment, led to the adoption of the existing plan.

### 60-CYCLE GENERATORS

There are now installed four three-phase generators, each rated at 36,000 kva., 80 per cent—100 per cent power factor, 13,800 volts at 80 deg. cent. temperature rise on the armature and field. The generators are insulated throughout with Class B material. While it was not believed that machines of this size and importance should be operated continuously at the 80 deg. cent. temperature rise, it was decided that excitation should be provided to permit development of the rating corresponding to this rise for use during peaks or emergencies. Normal operation at approximately

28,000 kw., 90 per cent power factor falls within the 60 deg. cent. temperature rise on both armature and field, generally accepted as conservative design practise for this class of insulating material.

The generators are of the overhung rotor type with water-cooled guide and thrust bearings combined in a single housing below the rotor; the guide bearing and the thrust bearing are of the adjustable segmental shoe type; the thrust bearing is designed to carry a total weight of 1,500,000 lb., including a water thrust of 1,100,000 lb.

These machines are designed to withstand overspeed to 231 per cent of normal, which value, like that of the water thrust, is somewhat greater than usual on account of the characteristics of the Kaplan turbines.

The generators are 29 ft. 2 in. in diameter and are 29 ft. in height measured from the lower face of the coupling to the top of the Kaplan head. The weight of a complete machine is approximately 400 tons.

The manufacturers of the generators cooperated in the design of the machines in order to make parts interchangeable as far as possible. Those parts exposed in the generator room are identical in appearance.

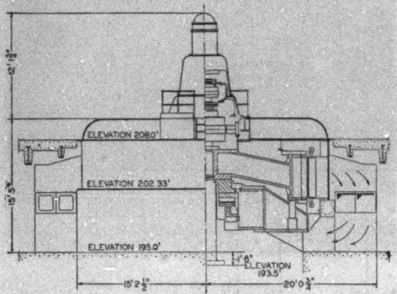


Fig. 10—Typical Cross-Section Through a Generator

A closed system of recirculating air is employed for cooling the main units. Air is introduced below the rotor and is forced by fans attached to the rotor through the windings into an eccentric frame, which serves as a duct to collect and conduct the hot air to the surface air coolers located on diametrically opposite sides of the machines, Fig. 10. The air path is totally enclosed throughout; the ducts are equipped with louvres which may be opened as required to bleed air for heating the generator room. A gravity system of water supplied from the forebay serves these coolers. The closed system of ventilation was selected rather than open ventilation for the following reasons: reduction in space; better control of generator temperatures; better fire fighting possibilities, and the exclusion of foreign material (particularly construction dirt).

The direct-connected pilot exciters are provided with slip rings from which power is taken to drive the governor fly ball motors. These operate at three-phase, 163 volts and 7.27 cycles.

The $CO_2$ system of fire protection is used, as well as a water sprinkler system.

## 13.8-Kv., 60-Cycle Bus

On account of the high ampere capacity of the main 230-kv. transformer banks, it was necessary to make the main buses of extremely heavy construction. Each consists of eight 4 in. by ¼ in. copper bars arranged in a modified hollow square configuration.

All taps from the bus to the oil circuit breakers, bus potential transformers, and bus ground switches are made of copper bar. Considerable difficulty was experienced in securing a satisfactory design for connecting these taps to the bus due to the bus-bar arrangement and the restricted space; this was solved by placing a 90-deg. twist in the bus-bars where these taps were made.

In order to secure high-speed oil circuit breaker operation on the 230-kv. transformer banks, and at the same time obtain sufficient current carrying capacity, it was necessary to use two 3,000 ampere oil circuit breakers in parallel. To insure a satisfactory division of load between these two breakers, the copper connections were designed to tap the bus at one point, and from this point to run over equally dimensioned paths to the oil circuit breakers, from which point they again converge. The tap to the transformers was then made at a point equidistant between the two oil circuit breakers; the bus supports are of the 25 kv. class; all insulators are designed to withstand a stress of 6,000 lb. at the center of the clamp. They are spaced, on an average, about 4 ft. 4 in. apart. Flexible expansion joints are placed in the bus at intervals of approximately 50 ft.

The bus, and its connected equipment, is designed to operate ungrounded; therefore, the generator neutrals have been grounded only through potential transformers to which are connected ground indicators. The value of the isolated neutral lies in the fact that simultaneous grounds must be present on two phases before a short circuit can occur. It is hoped that the use of high insulation values and sensitive ground detectors will prevent the occurrence of this.

Isolated neutral operation has been practised successfully at Holtwood for over twenty years. At Safe Harbor, single-phase bus grounds encountered during the preliminary operating stage were cleared on two occasions without disturbance.

*Oil Circuit Breakers.* Oil circuit breakers are insulated for 25 kv. and are designed successfully to interrupt 1,500,000 kva. at 13.8 kv. They are cell mounted with each tank in an individual concrete cell. The mechanisms are located on the floor adjacent to each breaker.

The generator and 69-kv. transformer breakers are rated at 2,000 amperes, and have normal speed of operation. The 230-kv. transformer breakers are rated at 3,000 amperes (two are used in parallel) and have a guaranteed opening time from application of tripping current to clearing of arc of 8 cycles. The bus tie and bus section breakers are rated 4,000 amperes, and are designed to open at normal speed.

The oil circuit breakers are mechanically interlocked with their isolating disconnectors. Interlocking is further carried on throughout the high-voltage electrical areas where the Cory system is used to lock switches and bus doors on 13.8 kv., and switches on 69 kv. and 230 kv.

Special precautions were taken to isolate the oil circuit breakers at Safe Harbor. These breakers are located in separate rooms; in general, not more than four breakers in a room. $CO_2$ protection is provided for these rooms, and oil sumps below each breaker tank are drained to the tailrace.

*Disconnecting Switches.* All disconnecting switches are mounted on insulators interchangeable with those supporting the bus runs and taps. The disconnecting switches isolating the oil circuit breakers are designed so that the six poles are operated by one mechanism. When in the open position they are swung into ground clamps, thus isolating and grounding the breaker.

### 230-Kv. Transformers

There are at present two 230-kv. transformer banks. Each of these transformer banks has a normal self-cooled capacity of 84,000 kva., and a capacity with its blowers in operation, of 126,000 kva. One bank only is now complete with blowers; blowers are omitted on the second bank, as it is installed at present as an emergency spare bank.

The three single-phase units comprising each bank are located in individual cells, and are Y-connected on the 230-kv. side and delta-connected on the 13.8-kv. side. The high-voltage neutral is at present solidly grounded, but the installation is such that the banks may be grounded later through an impedor of such size as will hold the transformer neutral voltage below 76 kv. Four 2½ per cent taps are provided and located in the high tension winding; two above, and two below 230 kv.

These transformers are of the combined gas filled-conservator type in which a 16-in. nitrogen filled space, directly below the cover, is kept under positive pressure by the head of oil in a standard conservator. Expansion and contraction is taken care of by variation of the conservator oil level. They may be operated as standard conservator transformers, if desired.

The transformers are insulated to withstand an induced test of 461 kv. Their windings and bushings are designed to be coordinated with each other and with a 64-in. protective gap located on the high-tension structure directly adjacent to the transformers.

Each transformer is protected by a thyrite lightning arrester located on the power house roof adjacent to the transformers.

### 69-Kv. Transformers

There are at present two 69-kv., three-phase, 30,000-kva., self-cooled transformer banks, inertaire type, equipped with blowers to increase this rating to 45,000 kva. They are equipped for tap changing under load over a range of 10 per cent above and below 66 kv.

Each transformer is protected by an autovalve lightning arrester located on the roof close to the transformer leads. Protective gaps are not used at this voltage.

### 230-Kv. Substation

The tentative 230-kv. layout provides for double buses, with three breakers per position. The use of the so-called "breaker-and-a-half" scheme permits handling three transformer banks and five outgoing circuits with maximum flexibility and minimum space.

The initial installation in the 230-kv. substation is scheduled to coincide with the installation of the second 230-kv. line to Baltimore. This, however, is expected to consist of only a tie breaker, its isolating disconnectors, and line disconnectors. These will be so located as to fit into the ultimate design.

### 69-Kv. Substation

For this substation, it is proposed to use a double bus scheme, with selector breakers for each line and transformer. This substation will be adjacent to the 230-kv. substation and, for topographical reasons, one of the buses will be folded back upon itself. This actually has the advantage that it is possible, with the use of one bus section oil circuit breaker, to operate split high tension on three separate customers.

### 60-Cycle Substation Control

A common control room housing a complete switchboard and battery will be located at the substation site. Miniature control will be superimposed on this, and carried by means of telephone cables to the main switchboard room in the power house, so that it will be possible to perform switching operations from the power house normally, and in case of trouble from the substations directly.

### 25-Cycle Generators

These generators, which are proposed for unit spaces Nos. 1 and 2, will be rated 37,500 kva., 80 per cent power factor, 107.1 r.p.m., 13,300 volts, single-phase, 80 deg. cent. temperature rise on armature and field. They, also, will be of the overhung rotor design and will be equipped with direct connected main and pilot exciters. The closed system of ventilation will be employed.

The rotors will be equipped with heavy squirrel cage windings and the stators will be spring mounted to absorb the pulsating torque resulting from single-phase operation. These generators will probably be the largest 25-cycle, single-phase waterwheel units in this country.

Due to space limitations, it has been necessary to restrict the outside diameters to 30 ft. 8 in. This has resulted in an unusually high rotor design, and will require the introduction of air at both the top and bottom of the generator. Two sets of coolers are proposed on each end of these generators, each set being the same size and interchangeable with the sets on the existing 60-cycle units.

### FREQUENCY CHANGERS

The frequency changers will be of the horizontal shaft, four bearing type, designed to operate at 300 r.p.m. The generator will be spring mounted and will be rated at 25,000 kw., 80 per cent power factor, 13,300 volts, single-phase.

These frequency changers will be of the outdoor type. The closed system of ventilation will be employed, and the heat removed by the same type of surface air coolers as are employed on the vertical machines.

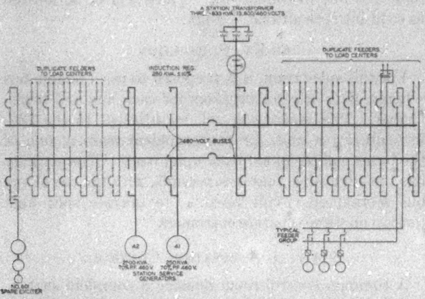

A STATION TRANSFORMER
THREE-833 KVA. 13,800/460 VOLTS
DUPLICATE FEEDERS TO LOAD CENTERS
INDUCTION REG. 250 KVA. ±10%
DUPLICATE FEEDERS TO LOAD CENTERS
460-VOLT BUSES
TYPICAL FEEDER GROUP
A2
A1
2500 KVA. 70% PF 460 V.
2500 KVA. 70% PF 460 V.
STATION SERVICE GENERATORS
NO. 601 SPARE EXCITER

FIG. 11—SINGLE-LINE DIAGRAM, 460-VOLT STATION SERVICE BUS

Cable terminals, field rheostats, and auxiliary equipment will be housed in rooms built within the foundations below the machines.

### 460-VOLT AUXILIARY SYSTEM

The major auxiliaries at Safe Harbor are supplied at 460 volts from two 2,500-kva., 70 per cent power factor, 180 r.p.m., waterwheel driven, umbrella type house generators, and a single-phase transformer bank of 2,500 kva. capacity, stepping power from the main bus at 13,800 volts to 460 volts.

There are two station service buses, each of two sections, complete with section switches and one bus tie switch (Fig. 11).

Positions are available for connecting each of the house units and the transformer bank to either bus; truck type breakers are used; however, three trucks only are furnished at present for the six generator-transformer positions. Normally, one house unit is connected to each bus. The transformer bank is made available to one bus by placing its truck breaker in position on that bus. In case it is desired to transfer a house unit or transformer from one bus to the other, this can be done through the bus tie, or by actually transferring one of the other trucks to the empty selector position.

In general, duplicate feeders run from these buses to auxiliaries throughout the station. The more essential auxiliaries, such as governor pumps and spare exciter, are served by feeders having few auxiliaries on them. The more general auxiliaries are served from distribution groups, a number of which may be connected to a pair of feeders. The more essential feeders are connected to those sections of the bus supplied by the house units.

Each individual motor is equipped with an across-the-line starter rated at least 25 per cent in excess of the motor horsepower, and provided with thermal relays for overload protection. A safety switch is provided for feeder selection and isolation for maintenance, and this is fused as short circuit protection. The rupturing capacity of these fuses is normally ample on the system to which they are applied; however, they are backed up by the carbon circuit breakers on the feeders which have a rupturing capacity of 40,000 amperes.

The station service buses are isolated from each other. Each is contained in a steel structure, the two buses being separated by a 7 ft. aisle. A gantry crane spanning the aisle and supported from the steel bus structures is provided to facilitate handling of trucks.

Generators, transformer, tie and section breakers are of 4,000 amperes capacity. All feeder breakers are of the truck type. These switchboards are so interlocked that it is not normally possible for a man to get at live parts.

### EXCITATION SYSTEM

The unit system of excitation has been adopted, supplemented by a motor-driven spare exciter supplied from the station auxiliary system. Each of the main generators receives excitation from a 185-kw., 250-volt main exciter and pilot exciter, both mounted above and direct-connected to its generator. Provision is made for the future addition of a second spare exciter, if found necessary. A transfer bus and the necessary air circuit breakers are installed so that excitation for the main units may be obtained from either the direct-connected exciter or the spare exciter.

Generator main field rheostats are not required, as the generator voltage is controlled by varying the fields of the main exciters. The excitation system is designed for a moderately high rate of response of the order of 100 volts per second. Parallel fields on the main exciter are used to produce this value. An auxiliary field, on which the excitation may be reversed as desired, is provided in each exciter to take care of sudden major changes in voltage. The excitation of each unit is controlled by a high-speed voltage regulator.

### LIGHTING AND SMALL POWER SYSTEM

Power for lighting and small auxiliaries is obtained from two 300 kva., three-phase, 460/208-120-volt transformers. Distribution is at 208 volts, three-phase for the smaller auxiliaries (motors 1 hp. and less). Lighting distribution is at 208-120 volts, three wire.

Exit lights and some of the control room lights are supplied direct from storage batteries. A number of bracket lights in the generator room and a percentage of the lights in the electrical bay can be transferred to the emergency lighting battery in case of failure of the a-c. supply; 32 volts, single-phase alternating current is used for wheel pit lighting.

Two 20-kva., 20-ampere series lighting transformers are installed for lighting the walkway on the dam and skimmer wall, the intake deck, the approaches to the power house, and the operators village.

### CONTROL

In this station 250-volt control is employed. Duplicate batteries, each with an eight hour discharge rate of 95 amperes to 1.75 volts per cell, are provided. These are equipped with a tap to permit their use for auxiliary lighting at 250-125 volts, three wire. Normally, one battery is used for control, the other for emergency lighting and other miscellaneous d-c. requirements.

A 15-kw. charger is provided for the control battery. A 30-kw. charger, consisting of two generators driven by one motor, is used to equalize the charging on the lighting battery, and a 30-kw. single generator set is provided as a spare unit for both chargers. Switching and control for batteries and chargers, and switches for d-c. distribution are housed in a dead front steel switchboard.

D-c. distribution at the main switchboard is handled from duplicate control buses through dead front disconnecting fuses housed in distribution cabinets. These are located in the terminal room below the switchboard, there being one such cabinet for each piece of major electrical equipment.

### MAIN GROUND SYSTEM

The island in the center of the river offered an excellent location for ground electrodes, but it was a considerable distance from the power house. However, four ground mats, each consisting of approximately twenty rods connected to two 500,000-cir. mil cables by a network of 4/0 cable, were located on this island, and single lengths of 500,000-cir. mil cable, 300 ft. in length, were placed along the face of the dam. Inasmuch as this entire area is submerged, great care was taken to thoroughly braze all joints, and to break the network into a number of parts, the terminals of which were brought in through the face of the dam and connected together inside by two 500,000-cir. mil cables running through the inspection tunnel. The loss of one or more of these incoming feeders from the network should not seriously reduce the protective value of the ground.

In order to obtain a direct path for lightning arrester grounds, a number of 1,000,000-cir. mil cables were carried from the lightning arrester location on the roof, out into the forebay, and terminated in connections to heavy rail sections. These cables were connected to gate guides and other submerged metal passed on the way to the forebay. It is expected that the amount of contact surface offered will give a fairly low resistance.

At the shore end of the power house directly adjacent to the rock fill on the railroad is a section of quiet water. It is expected that considerable silting will take place at this point; therefore, a network of cables, with a backbone of 500,000-cir. mil feeders, is laid here.

Two 500,000-cir. mil cables join the ground mats on the island with those in the forebay and those in the shore end of the forebay. In addition, heavy 5-in. by ¼-in. copper buses in parallel with these cables connect all grounds in the power house area. From these heavy buses are run auxiliary grounds to all sections of the station. The transformer banks are directly connected by short loops to the cables from the lightning arresters to the forebay. This brings the transformer tanks and lightning arresters very close together electrically.

The transmission line ground wires are tied to the power house grounding system at several points in the vicinity of the power house.

### COMMUNICATION

A Bell telephone system with a central exchange located in the control room is used for telephone communication throughout the power house. This is supplemented by an autocall system with stations located throughout the power house, dam, and substations, and by an operating order signal system between the switchboard and the turbine gage boards on the operating floor.

A system of telephone annunciator drops is used to advise the operating staff of unusual operating conditions. One large annunciator board in the control room covers all major machinery, while another of equal size is used to indicate operation of the $CO_2$ fire system, and, by thermostatic actuation, the location of fires in the electrical bay. Each unit gage board is equipped with an annunciator which shows the operations of the equipment connected with that unit.

### RELAYS

The main and house generators are equipped with differential relays which shut down the unit completely. They are, also, equipped with overspeed and overvoltage relays with contacts in series. These act to open the main and field breakers and shut the unit down to speed no load.

Provision is made for the installation of differential protection on the main buses; however, this protection is not yet installed.

The main transformer banks are equipped with differential relays, which protect a zone between the high-tension bushing current transformers and the low-tension bus. The 230-kv. transformers are, also, equipped with a high-tension winding differential scheme.

As each of the main transformer banks is connected directly to a line, line and transformer protection is somewhat correlated. High-speed impedance relays are used as protection against phase-to-phase faults. These are backed up by straight overload relays. Inasmuch as there are at present no high-tension buses on the system, ground protection is secured by the use of relays connected in the neutrals of the power transformers.

Counters are installed on the main annunciator board to record the number of operations of each of the main relays.

### TURBINES—MAIN UNITS

An outstanding feature of the plant is the Kaplan turbines, the blades of which are adjusted automatically as the load changes, to maintain high efficiency over a wide range of load; also, the relation between blade angle and gate opening can be varied manually to compensate for changes in head.

The turbines selected for this installation are of the Kaplan type, with automatically adjustable runner blades. The selection of this type of turbine followed an extensive investigation covering turbine units equipped with the four principal types of runners, namely, the Francis type, the propeller high-speed type with fixed blades, the propeller high-speed type with manually adjustable blades, and the Kaplan high-speed type, as selected for this project, with automatically adjustable blades. Typical horsepower efficiency characteristics for the Francis type, the fixed-blade propeller type, and the adjustable-blade propeller type runners are, in general, about as indicated by the curves shown in Fig. 12, under normal head operating conditions.

The investigation made covered various types and combinations of types of runners, too numerous to describe in this paper, but a general statement of the conclusions reached may be of interest.

The Francis type of runner, which in the past has been extensively used for operation under low and medium heads, was carefully investigated, but could not be justified for this installation, in view of the low power output in relation to the cost of the power house, and in view, also, of the high cost of the low-speed generator equipment required.

To overcome these objectionable features, the propeller type of runner with fixed blades was considered. The higher power capacity and higher speed of this type runner, together with its simplicity and low cost of construction, appeared to offer attractive possibilities. However, with the propeller fixed blade runner, the efficiencies drop off rapidly as the load is varied above or below the point of maximum efficiency and, as a result, inefficient use would be made of the water under such conditions.

Propeller type runners with manually adjustable blades were considered as a possible means for obtaining greater economy in the use of water and, although greater economy would actually be secured from this type of wheel with a fixed load on the station, and greater capacities would be obtained under reduced heads, no particular advantage would be gained under the varying load conditions which exist at Safe Harbor.

To eliminate the objection of poor economy under varying loads, an investigation was made of the use of one Kaplan unit with governor adjusted runner blades, in combination with five propeller fixed blade runner units. The horsepower-efficiency characteristic of the Kaplan runner is quite flat and, consequently, high efficiencies are maintained as the load on the unit is reduced. With such a combination of units, and with the propeller fixed-blade runner units all operating at best efficiency and the Kaplan unit taking the load swings, reasonably good economy in the use of water may be secured. The economical advantage of this combination of units over the combination of six propeller fixed blade runner units is indicated by the horsepower-quantity curves shown in Fig. 13. It will be seen that with this latter combination, the inefficient zones below the scalloped portions of the curves are very nearly eliminated, and the curve very closely approaches a straight line. With the introduction of the Kaplan unit, the economical performance in the use of water under both fixed and varying load conditions appeared very satisfactorily.

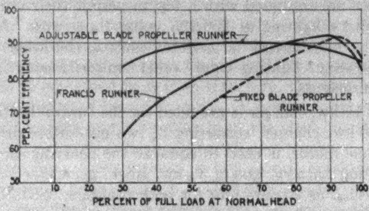


FIG. 12—POWER/EFFICIENCY-COMPARISON OF ADJUSTABLE BLADE, PROPELLER, AND FRANCIS TYPE TURBINES

It should be understood that Kaplan runners with their adjustable feature may be operated with the blades wider open than the fixed blade position on the propeller runner. Consequently, for a given wheel diameter, the Kaplan runner will have a higher maximum power, or, with the same power, a smaller runner diameter with a corresponding reduction in the spacing between units may be secured. The higher capacities are, of course, contingent on the runners being set sufficiently low for these capacities to fall within the power limits set by cavitation.

The curves in Fig. 12 were based on the various types of runners all having the same maximum power capacities and, consequently, the fixed blade propeller and the Francis runners are of greater diameter than the Kaplan runners.

The advantage in size of Kaplan units results in a smaller and less expensive power house structure and was an important reason for the final selection of six Kaplan adjustable-blade runner units, similar in size and design and having the same power ratings.

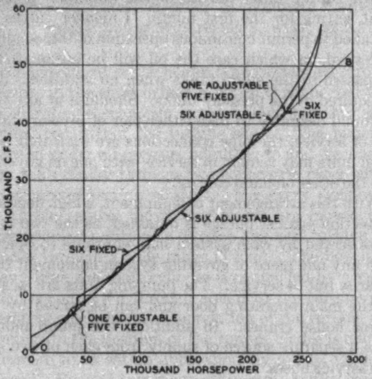


Fig. 13—Power Discharge Relation of Propeller and Adjustable Blade Turbines

Other advantages to be gained from the use of all Kaplan units, in place of other types and combinations of types, include the greater capacities obtainable with the adjustable blade in seasons of high flow, when the head is reduced below normal by a rise in tailwater level; convenience in operation, resulting from identical control features and performance characteristics, and interchangeability of parts, which makes possible the use of only one set of major spare parts for all units.

It may be of interest to know that for turbines of small size, the difference in first cost between Kaplan turbines and turbines with propeller fixed blade runners is appreciable, but as the turbine size increases the percentage difference becomes less, and for units of the size selected for Safe Harbor, becomes small and is practically negligible when considered in connection with the total cost of the development.

It may further be said that the units in this station are required to furnish energy over two separate systems, and it was decided that at least two Kaplan units should be installed for each system group, so that one will be available at all times for economical regulation of the load, should the other unit be shut down for inspection or repairs. On the basis of this requirement, it appeared that four Kaplan units should, in any case, be the minimum number considered. These are the highest powered Kaplan turbines in the world; the runners are 18 ft. 4 in. in diameter, and will discharge about 9,000 sec.-ft. at full gate and normal head. To minimize cavitation, these runners are set with their centerline 7 ft. below normal tailwater level. This location of the runners with relation to tailwater elevation was determined by exhaustive model tests in the Holtwood Hydraulic Laboratory of the Pennsylvania Water and Power Company, as described in a contemporary paper.*

Two means of unwatering the wheel casing have been provided. In the one scheme the tailwater can be lowered automatically by admitting compressed air to the wheel casings. As the gates on these units approach the no-load position, an air valve will open and admit compressed air to the wheel casing. If the gates are closed, as when running reserve, or as a synchronous condenser, air pressure will be maintained automatically in the wheel casing and depress the water level below the runner.

The alternative method of unwatering the turbines for inspection or maintenance is to put stoplogs in the discharge end of the draft tube and pump out the water with portable 10,000-gal. per min. unwatering pumps.

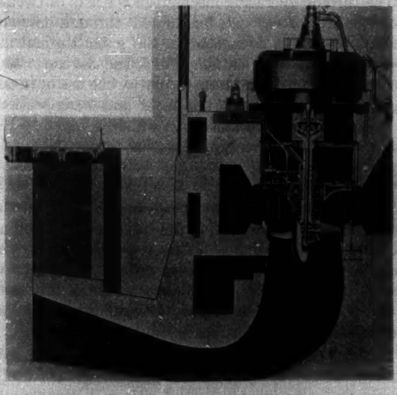


Fig. 14—Typical Section Through a Unit

The speed rings are of cast iron in four sections, containing a total of 20 stationary vanes cast integrally with the upper and lower rings. The overall diameter of the speed ring is approximately 28 ft. 10 in.

The speed ring and stationary speed ring vanes are cored hollow, and provision has been made for the introduction of steam inside the vanes as a protection against

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**Safe Harbor Kaplan Turbines*, by L. M. Davis and G. W. Spaulding.

the accumulation of frazil ice. Provision has also been made for the discharge of steam into the scroll cases, after these passages have been unwatered, to aid in dislodging any frazil ice which may have formed, and, also, to sterilize the wheel pits before men are permitted to carry on extended work therein.

The runner hub is normally submerged, and, for the lubrication and protection of the operating mechanism within the hub against corrosion, the hub is completely filled with a heavy grade of oil. The quantity of oil required for each runner is approximately 1,100 gals.

The turbine guide bearings are of the babbitt lined, oil lubricated type. One belt driven pump is used to circulate the oil in normal operation. A motor-driven pump, also, is installed to start automatically through the action of a flow meter, should the flow of lubricating oil in the supply line be reduced to the minimum quantity required for proper lubrication. These bearings are located below tailwater, and are protected by stuffing boxes.

Water leakage is discharged into the station sump well through two motor-driven pumps mounted on the turbine head covers, one of which is a spare pump. The spare pump is arranged to start automatically through the action of a float switch should the water in the space around the bearing rise to a dangerously high elevation.

The turbine operating mechanism consists of twenty movable cast steel gates actuated through two oil pressure cylinders connected to the gates through an operating ring and suitable links and levers. This mechanism is protected from injury by the use of shearing pins inserted through the upper and lower sections of the gate lever, one section of which is keyed to the gate stem. Fig. 14 is a typical section through a unit.

## GOVERNORS AND PUMPING SYSTEMS—MAIN UNITS

The governor equipment is required to perform the double function of regulating the speed and controlling the pitch of the runner blades. Consideration was given to the following features: degree of protection against outage of the units due to failure of any part of the governor system; sensitive regulation of speed; convenience in operation; space required.

Three types of governor systems were considered, namely; the unit system, providing for one governor and one pump operating separately with each main unit; the central system, providing for oil being furnished to all governors from a central battery of pumps; and the twin system, providing for the operation of two adjacent main units from one small central system located between the two units being served.

The twin system was adopted, and includes for each pair of units; two governors, two motor-driven pumps, two pairs of pressure tanks, and one sump tank with two compartments common to both units.

The governors are of the oil pressure actuator type with motor-driven flyballs. They are of light construction, a desirable characteristic for sensitive operation and quick response to changes in speed.

The pumps are of the herringbone gear type, motor driven. This equipment is so interconnected that one pump may be used for the operation of either one or both of the main units and the second pump held in reserve as a spare unit. Each pump is equipped with a pressure starting switch to provide for the automatic starting of the pump held in reserve should the pressure in the supply tanks fall below the minimum pressure limit setting for the first pump. Unloader valves are installed to permit continuous operation of these pumps, if desired, in which case the oil will be automatically by-passed to the sump tanks when no additional fluid is required in the pressure tanks. Should it at any time be found desirable to take either pair of pressure tanks out of service, the pipe connections are such that both main units may remain in service, with one on governor and the other on hand control.

With this arrangement of equipment, a high degree of protection against outage is obtained, as the two main units served by each system may continue to operate with any one piece of governor system equipment temporarily out of service. The pumping units are located on the main operating floor and can be served by the power house cranes. In addition, the pump motors have a separate source of supply from each of two station service buses.

Each governor is equipped with a safety shutdown torque motor and solenoid switch, to provide for automatic closure of the turbine gates to either the speed no-load or completely closed position through the operation of any one of a number of protective relays.

The characteristics of the torque motor are such that it will not permit the opening of the turbine gates beyond speed no-load position until the voltage has reached from 50 to 60 per cent of normal, at which voltage the flyballs will assume control, except by hand through the release of a mechanical lifter. It is designed, also, to prevent the gates from opening when starting up should one phase of the three-phase governor flyball motor circuit be open. After the motor has been placed in service, the gates will be automatically closed when voltage drops to approximately 40 per cent of normal, but will remain open, with one of the three phases of the governor supply open, should the voltage remain approximately normal.

The governor flyball motors are connected to the pilot exciters on the main unit shafts through slip rings, and operate at 163 volts, 7.27 cycles.

A unit may be quickly shifted from governor to hand control, or vice versa, by the throw of a single lever.

As these units are of the adjustable-runner blade type, the capacity of the pumps and tanks is more than double the capacities required for fixed-blade turbines of the same power and head. The capacity required for operation of the turbine gates at the normal pressure of 200 lb. is 457,000 ft.-lb., and for the operation of the runner blades, 685,000 ft.-lb., making it necessary for the pumps and tanks to provide for a total operating capacity of 1,142,000 ft-lb. The pressure and discharge piping at each governor, as well as the piping from the runner blade control valve to the oil head at the top of the unit, is 10 in. in diameter. Each of the four pressure tanks in one twin system is 7 ft. in diameter and 12 ft. high.

Oil was selected as the governor pressure medium in preference to water, in order to eliminate corrosion; also, to reduce power requirements, wear, and valve friction.

The movement of the blades is accomplished through a piston, in the shaft cylinder, which is connected with the operating mechanism in the runner hub through a vertical rod within the turbine shaft. The piston is operated under oil pressure admitted to and discharged from the cylinder through two concentric pipes within the generator section of shaft. For every position of the turbine gates, the runner blades are moved to a corresponding position to develop the best turbine efficiencies through a wide range of load. The flow of oil to and from the shaft cylinder is controlled by a valve, which is connected through a cam to the turbine gate operating mechanism. The relation of the turbine gate openings to the position of the runner blades is allowed to remain fixed within approximately a 4 ft. variation in head. Beyond this range other cams, which may be quickly and conveniently shifted into position, are employed to insure reasonably high efficiencies under a wide variation of head.

### HOUSE UNITS

Located in the ultimate center of the station are two house turbines of the Francis type, rated at 3,100 hp. at 180 r.p.m. under a 55-ft. head. They possess no unusual features not mentioned in connection with the main turbines.

The turbine casings are of the steel plate lined scroll type. The draft tubes are of the straight conical type, lined with heavy plate steel in the vertical sections.

### GOVERNORS—SERVICE UNITS

The governors for these units are of the self-contained oil pressure type, with the gate operating cylinders mounted on the governor base; energy is taken from the pilot exciter for the motor driven flyballs. One pumping unit is provided with each governor mounted with its pressure and sump tank on a common baseplate. Normally each pumping unit will serve its own governor, but the equipment is interconnected and of sufficient capacity that one pump can satisfactorily operate both governors. In flexibility of service, the arrangement of governor drives and pumps for these units is similar to the twin system used for the main units.

### STATION AUXILIARIES

In general, the station auxiliaries are located at the shore end of the station; this was done primarily to reduce operating costs; due to the nature of the power house site, the space was available at relatively low cost. There is provided the usual complement of hydro station auxiliaries, and as they presented no unusual features, the principal auxiliaries will be described very briefly.

*Air-High Pressure System.* This is provided for charging the governor pressure tanks and for operating the generator brakes.

*Air-Low Pressure System.* This is installed to furnish air principally for pneumatic tools; depressing the level of the water in the draft tubes for synchronous condenser operation of the units; and the air bubbler ice protection system on the dam.

*Oil Purification System.* One central oil purification system, with two centrifuge separators provide for the purification of all oil. One centrifuge is used for transformer and circuit breaker oil; the other for the governor and lubricating oil.

*Raw Water Supply.* A 24-in. main, with two screened intakes taking water from the forebay, is installed to serve all raw water requirements. The principal demands for raw water are the generator air coolers and thrust bearings. Water is supplied, also, to each set of generator air coolers through an 8-in. line, taking the supply from the intake of that particular unit, as well as through connection to the raw water main.

*$CO_2$ Fire Protection System.* $CO_2$ gas was selected as the means of extinguishing fires in enclosed areas. A central system, with appurtenances, has been installed. This system is installed on the generators, oil circuit breakers, and in the oil storage and purifying rooms.

*Vacuum Cleaning System.* A central vacuum cleaning system affords a convenient method of cleaning the interior of the station. There is a total of 223 wall and floor valves located throughout the station, all being served by one vacuum cleaner unit, centrally located.

*Water Filtration Plant.* A small filtration plant is located within the power house building to serve the requirements of the station, as well as of the operators village nearby. This filter is of the rapid sand gravity type, with two 50-gal. per min. filter compartments.

*Heating and Ventilation.* The office end of the power station and the control rooms are steam heated by oil fired boilers in the shore end of the building. Two water tube type boilers are installed, each with a normal rating of 100 boiler hp. The capacity of one boiler is sufficient to carry the normal heating load. The overload rating of the boilers, however, is such that an ample supply of steam will be available for steaming the turbine units for the removal of frazil ice.

The heating of the generator room is accomplished by the use of heated air, bled from the generators through louvers in the housing. The electrical bay is heated by the same air, distributed through a series of fans and air ducts to and from the various compartments.

### GENERAL

Application for a license was made to the Federal Power Commission on October 9, 1929, and was granted on April 22, 1930. Application for a certificate of Public Convenience was made to the Public Service Commission of Pennsylvania on January 10, 1930; this was granted March 31, 1930. Application was made to the Water and Power Resources Board for a Limited Power Permit on October 14, 1929, which was granted January 22, 1930.

The delivery of power to Baltimore from the first unit began December 7, 1931, 20 months and 7 days after active work was started on the project site—an outstanding achievement in the annals of hydroelectric construction. The drought that prevailed during the construction period and the absence of high floods were important contributory factors to the speed with which the work was executed.

In the average year, the Safe Harbor plant will generate over 800,000,000 kw-hr.

The design and engineering, acquisition of property, and negotiations with regulatory authorities were carried out entirely by the company's organization. The dam, power house, and relocation of the C. & P.D. Railroad were constructed under contract. The power company's construction organization installed all power plant equipment.

### ACKNOWLEDGMENT

The author desires to express his appreciation to his associates for the assistance rendered in compiling the material contained in this paper.

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## Discussion

**J. R. Baker:** Probably the feature of advanced design most apparent to a reader of the paper is the use of the Kaplan turbine. However, the advantages secured by its adoption are not the only results of the progress in hydroelectric design that have occurred in recent years. A comparison of the cross-section, Fig. 6, with one of the Holtwood plant, located 7 miles below Safe Harbor and designed some twenty years earlier, will show a striking economy of building volume in the design of the Safe Harbor plant. In addition to an actual conservation of volume, the building mass and structure are applied to better purpose by more skillful arrangement. The great advance in hydraulic design is well illustrated by the fact that the controlled water path through the Safe Harbor plant is twice as long horizontally as that in the Holtwood plant, notwithstanding the smaller dimensions of the Safe Harbor plant. The operating heads are equal at the two plants. The dimensions referred to are as follows:

|  | Safe Harbor Plant | Holtwood Plant |
|---|---|---|
|  | Feet | Feet |
| Upstream face to downstream face | 187-11½ in. | 196 |
| Width of space under roof | 105 | 175 |
| Screens to outlet of draft tube | 168 | 85 |
| Center line of units to outlet of draft tube | 72 | 38 |
| Longitudinal spacing of units | 62 | 42 |
| Horsepower of units | 42,500 | 13,500 to 20,000 |

The designers of the plant undoubtedly considered the omission of a superstructure over the generators, and it would be of interest to know the reasons that lead to an inclosed generator room.

**P. M. Hess:** Safe Harbor today has been in operation for a little over 10 months. In connection with the papers presented it may be of interest to outline briefly the operating experience, good and bad, so far obtained with the major pieces of equipment.

### ELECTRICAL EQUIPMENT

The 230,000-volt transmission line, approximately 70 miles in length, has gone through a normal lightning season and an abnormal winter storm with an excellent record, having not a single outage or disturbance. Since all of the 66- and 70-kv lines sometime during the season had momentary outages due to lightning, this confirms the experience obtained on other 230-kv lines built in recent years: that well designed lines of this voltage are distinctly superior in this respect to lower voltage lines. During the severe sleet, snow, and wind storm of March 6th, 1932 when circuits of all natures were out, and in many cases on the ground, this 230,000-volt circuit rode through without any trouble.

On each end of this line are single-phase transformer banks of 126,000-kva capacity built by two different manufacturers, both of which have had a very successful record and very small maintenance. At the Baltimore end of the circuit a spare phase is provided while at the Safe Harbor end, a complete spare bank has been provided.

The Safe Harbor main 13-kv bus installed in duplicate, capable of being tied and sectionalized, is operated ungrounded, the same as the Holtwood bus. Operating ungrounded on this bus has probably eliminated two disturbances or failures during the early operating period because in two cases rats were found electrocuted by the capacity current to ground, which was of sufficient magnitude to burn the rats severely and slightly damage the bus insulators, but did not sustain any arc. Indications of grounds on this bus are obtained by lights in the control room, which are operated from the secondary potential transformers, connected between the generator neutrals and ground.

High-speed voltage regulators are installed on all of the generators, including the station service units, and have to this date functioned satisfactorily, without reflecting any at present noted speed change to the governor fly balls due to phase shifting in the pilot exciters. However, on the station service units, very sudden voltage digs are periodically received on the service bus by motors of from 100 to 200 horsepower being thrown directly on the station service bus. This inrush current is of such a short duration that the regulator scarcely has time enough to function before the condition is rectified. Investigations are at present under way to determine some means of correcting this somewhat annoying dip in station service voltage.

Circuit breakers, 460-volt truck type 4,000 ampere, are installed on the main 460-volt bus for generator and transformer sectionalizing and tying purposes in place of the customary oil circuit breakers. There have been several cases when these breakers have had occasion to function and they have given no difficulty.

The telemeter type wattmeter installed on the main generators for transmitting purposes has given no trouble with the exception of the sockets originally supplied for holding the automobile type head lamps, supplying the necessary spot light. These sockets have been replaced with ones of a more conservative current carrying capacity and, by a slight reduction in the lamp voltage, have since given no trouble.

The elaborate annunciator system in the plant has not been in service long enough to present any definite information on its reliability. However, some difficulty has been experienced with short lamp life and difficulty to obtain lamps of equal brilliancy.

### Generators and Turbines

The generators themselves have behaved entirely satisfactorily. There have been failures of the combined generator and turbine thrust bearings three times on two of the units; in each case occurring during starting operations. The cause of these failures is not entirely clear. It is *our* opinion that they should be tied in with the peculiar starting characteristics of Kaplan turbines. When running at synchronous speed the hydraulic thrust on a Kaplan unit is a minimum at no load and a maximum at heavy load. During the starting period, however, the thrust load may reach values decidedly in excess of maximum running thrust that is at a time that the bearing is least able to stand the additional friction caused by the thrust. This fact is caused by the nearly horizontal position of the runner blades of the turbines during starts, and is different from the conditions existing in Francis turbines. It seems that this starting thrust is roughly proportional with the gate opening at which the unit starts. By making both the runner and shoes in the bearing exceptionally smooth a double purpose is therefore obtained; first, the starting friction itself is reduced; this means a smaller gate opening required to start; hence less hydraulic thrust, which again reduces the friction. At any rate this has been done and is believed to have remedied the condition as no failures have occurred after 51 starts on one of the units and 89 on the other since the last inspection.

The turbines at Safe Harbor are installed approximately six feet below the tailrace water level and it became necessary to provide some means for unwatering the draft tube quickly when condenser operation is required. This is accomplished by admitting compressed air to the turbine pit at a pressure necessary to blow the water below the Kaplan nose and maintain it at this level. Admission of the air is controlled by an automatic controller actuated by the closure of the turbine gates. The initial inrush of air is comparatively large but the make-up air, which is the result of turbine gate, packing gland and gate stuffing box leakage, is extremely small. So far this scheme has been comparatively satisfactory, although some slight improvements are contemplated.

Many hydraulic turbines of the nature as installed at Safe Harbor have a more or less common type of guide bearing, using lignum vitae or hard rubber, both water lubricated. The Safe Harbor units are equipped with an oil lubricated babbitt bearing and this has, to date, been very successful. On the station service units the rotation of the turbine provides the oil circulation, whereas, on the main units, a belt-driven oil pump is installed for normal operation and a motor-driven pump for starting and auxiliary purposes.

Directly beneath this oil lubricated turbine guide bearing is located the main turbine packing gland. Considerable difficulty was experienced with this packing originally, due to the pressure variations on the gland. The variation on this stuffing box is from approximately 10 inches of vacuum to 17 lb pressure, therefore requiring a very pliable packing, that is, one with yielding characteristics. The original packing contained lead wire insertions. However, this has since been supplemented with a braided packing thoroughly impregnated with graphite, which will probably be the solution.

After approximately six months of comparatively heavy loading on the turbines the blades show evidences of a slight amount of pitting. This is being followed up very closely and has been largely reduced by a slight amount of reshaping of the blades in the various sections where cavitation has been more active.

It is the characteristic of low head hydro plants to be capable of exceptionally quick starting. This holds good also for the Safe Harbor units. On one occasion, when the system frequency went slightly low, due to two small steam units falling out of step, three units were started and paralleled at Safe Harbor in a total elapsed time of four minutes, thus increasing the system capacity with about 84,000-kw capacity without any difficulty.

A small amount of oil leakage is occurring at the leather packing glands on the turbine blade shanks. However, on three of the units this is practically negligible, whereas, on the other unit, the leakage amounts to an appreciable figure. The reason for this abnormal oil leakage has been traced, supposedly, to the sticking of the gland follower. By a slight change in the design of the follower, having one solid ring in place of sections, this will probably be entirely eliminated.

### Dam and Other Appurtenant Equipment

The skimmer wall installed for the purpose of preventing the entrance of trash and cake ice to the power house section of the forebay has proved to be very effective, since no trash to date has entered this section. It is believed that since this wall was effective during the preliminary pond filling stages when the amount of trash is naturally excessive, that no trash trouble will be encountered in the future. It is true that with four units in operation the velocity through the wall is only one-third of that which will be encountered when the ultimate twelve units have been installed, but even with twelve units operating the velocity of the water through the submerged opening will be only 1.75 ft per sec, so no trouble of this nature is anticipated.

The first winter of operation was comparatively mild and no statement can be made at this time as to the effectiveness of the bubbler system installed on the dam to keep ice away from the skimmer wall and spillway gates. However, preliminary runs indicate that no trouble will be experienced along this line. An item of interest is the effectiveness of the regulating gates installed on the power house side of the dam, which are operated by mechanisms installed in the dam and remotely controlled from the control room. These gates were used extensively during the spring freshet and have been found to be very effective in maintaining a constant pond elevation by bridging over the discharge capacity gap between spill gates in any desired quantity. Some doubt was raised as to whether or not it was possible to throttle the spillway gates without damaging the bottom rubber seal. At least three or four of these gates were operated in this manner for comparatively long periods without the slightest indication of damage. These gates were held in the throttled position by the gantry cranes. However, one gate is provided with a latching mechanism to support the gate in steps of three feet and this feature has proved to be of material advantage in the regulation of spill water.

The turbine stationary vanes and pits have been equipped with a means for steaming in case of the presence of frazzle ice. Also, a boiler plant of very flexible capacity, has been installed to provide this steam. The installed capacity, according to tests will supply steam for approximately three units simultaneously. However, there has been no occasion to utilize this scheme. It is believed that the severity of frazzle ice runs formerly frequently present at the Holtwood plant, has been greatly reduced by the wiping out of the rapids above Safe Harbor. Safe Harbor should also be superior to the older Holtwood plant in this respect on account of the larger size of the units and the deeper intakes designed for low water velocities.

In general, all of the many schemes provided for making the operation of Safe Harbor comparatively easy, and with as few men as possible, have to date worked out satisfactorily.

The operating force consists of six men per shift, making a total of eighteen operators, with three additional men provided for sickness, vacations and days off relief. A comparatively small permanent electrical and mechanical maintenance force is maintained to cover routine inspection and repair work, making a total plant personnel of approximately thirty-five men, exclusive of the supervisory force.

**F. H. Hollister:** This paper as well as the others related to this subject bring out very forcibly the following:

1. The great improvement made in low head waterwheels since 1910 allowing now a much higher speed, lower total investment cost, and a higher average economy.

2. The great advantage to be gained by the modern interconnected system that permits output to be utilized at the off peak period when the stream flow is often ample for the total installed capacity of the hydro station, but in an isolated system would have load for perhaps not over 20 per cent of its generating capacity. *Without extensive interconnections* the full use of the kilowatt hours available cannot be made use of when there is ample water, and a water-power economically unattractive without the long interconnections becomes feasible with them.

3. The additional expense for the more efficient turbine is more than offset by the advantages to be gained, or in other words, the most efficient turbine makes the overall cost of power the cheapest.

4. The distinct advantages to be gained by laboratory tests under as near as practical to service conditions, from the standpoint of cavitation, stability, and efficiency.

5. From the very clear description of the electric system and the reasons given for many of the important elements, it is well brought out that the system has been designed to give a high degree of reliability.

The following comments are submitted:

*Flat Efficiency Curves.* It is interesting to note that in hydroelectric work it has been found of advantage to get a flat efficiency curve.

In the Chicago District it has been found in the last few years that better economies are obtained with steam turbines with flat economy curves giving high economy between 50 to 85 per cent maximum continuous load rather than with units having best economy at maximum load. Although at maximum load efficiency is less, the units are seldom run at such points, and when run at good economy at least 15 per cent reserve is always available.

*Necessity of Better Economy and Lower Investment Cost.* The improvement in steam-turbine and boiler room efficiencies made during the last ten years has made it imperative to improve the overall all day efficiency of the hydroelectric station or else greatly reduce the investment permissible in a low head hydro plant.

*Improvement in Steam Plant Efficiency.* In 1910 when the Holtwood plant went into operation the best economy in yearly operation of a steam turbine plant was about 23,000 Btu per net kilowatt hour. By 1922 that had been reduced to about 18,000 Btu, and equipment now available can produce a kilowatt hour for under 12,000 Btu.

*Advantages of Automatic Bus Protection.* The designers have very wisely made provision for installation of bus protection on the main busses, although this is not in operation initially. The excellent results obtained for some years on other systems by either differential bus protection or fault bus protection would seem to emphasize the advisability of putting one of these systems into operation on any station of the size of Safe Harbor when interconnected with other large stations. In two large stations that went into service and made good records before either of these protective methods had been tried out, either system when available would have later probably prevented a serious shutdown with resulting expensive damage, and it has been found advisable to install one method in the first case and the other method in the second, with satisfactory results. From the last five years' experience it seems advisable in any large generating station on a large interconnected system, in order to meet modern service requirements, to use one of the two types of bus protection, irrespective of whether the main busses are open, in masonry compartments of either adjacent or isolated phase, or whether the busses are of the metal-clad type.

**A. H. Hull:** While the paper gives a comprehensive description of the undertaking and its magnitude, there is a number of features on which comments suggest themselves, not in any spirit of criticism, but in order to bring out, at greater length, some of the considerations that led to the construction adopted.

The single-line diagram indicates that transformer banks are to be fed from the same 13.8-kv bus system. With two transmission system requirements to be met, this would appear to limit freedom of varying the generator voltage.

It is pointed out in the paper that the equipment assembly space, with the service and office space takes 136 feet in length. This is about 27 per cent of the length of the building occupied by the main units in the initial construction and about 17.5 per cent of the ultimate building.

It is interesting to note that at Safe Harbor the usual practise in the past with respect to cooling of generators and transformers has been reversed. Here the generators are water-cooled and the transformers are air-cooled and some definite advantages are gained. It would be of value to know the reasons for adoption of air-cooled transformers. In northern climates, where temperatures drop to 30 deg and even 40 deg F below zero, water-cooled transformers are in successful use.

Would the author indicate the main reasons for adoption of the "overhung" type of generator and show what reduction in building height was secured as compared with that required for the type with thrust bearing above the rotor. Accessibility of the thrust bearing when located above the rotor has been advocated by some operating engineers as a sufficient reason for not adopting the overhung type of machine.

While use of the pilot exciter for furnishing energy for the motor of the governor fly-balls is attractive, and has been successfully used, there is one case where it was not proved acceptable since any operation disturbing the excitation system reflected into the governor system and caused surging. This particular installation used an 8-pole 250-volt exciter operating at 100 rpm with a two-pole motor on the governor head.

The use of two 3,000-ampere breakers in parallel on the low voltage side of the 230-kv transformer bank is an effective scheme. It would be of interest to know if higher generator voltage, say, 22,000 to 26,000 volts, was considered.

Two separate low voltage windings on the transformers have been used in some plants to keep the ampere rating of the switching within reasonable values.

In connection with the generator fire protection adopted, what was the reason for installing the water system in addition to the $CO_2$ system?

Where the expansion joints are used on the 13.8-kv bus, how is the copper fastened to the insulators? The general practise, the writer believes, is to have a tight clamp at one insulator in a given section of bus while at the other insulators, a snug clamp which would allow the copper to slide and yet be tight enough to withstand the short-circuit stresses.

The method adopted for grounding the generator neutrals only through potential transformers has worked out very satisfactory in various plants and is to be recommended.

Was any provision made to ventilate the 13.2-kv oil switch rooms? The writer recalls one case where the room temperature dropped about 10-15 degrees after a simple ventilating system was installed.

In connection with the auxiliary service, it is noted that 460 volts was adopted. In a steam plant where the equipment is more or less concentrated, this voltage, in the opinion of the writer, may be justified. In a hydroelectric station, where the auxiliary equipment is much more disturbed and to greater distance, a higher voltage seems to be justified. Not only is there considerable saving in copper, but a more reliable service is obtained on account of the reduction of short circuit and the use of transformers reducing the auxiliary voltage, say, from 2,300 volts to 460-208-104 volts as required.

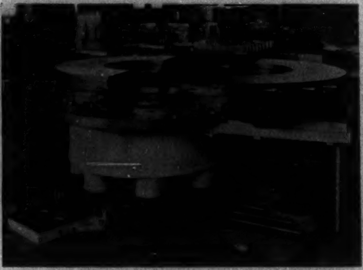

Fig. 1

Considerable study and expenditure has evidently been expended in connection with the main ground system, and it is well warranted. The writer recently installed a somewhat similar ground mat where the ground conditions were particularly bad, *i. e.*, mostly rock. A ground resistance was obtained of the order of one ohm. Would the author advise what ground resistance was obtained at Safe Harbor?

The writer wishes to acknowledge the assistance of Mr. T. R. Millar in preparing this discussion.

**Arthur B. Lakey:** The 82-in. pivoted segment thrust bearings at Safe Harbor carry a load up to about 1,500,000 lb apiece. The unit pressure on the 3,600 square inch net babbitted bearing shoe surface is accordingly 416 lb per square inch. The parts subject to possible damage in service, namely the tilting shoes and the runner plate, are interchangeable on all four units. The runner plate is split.

Speaking specifically of units Nos. 3 and 5, the shoes are positioned by a "shoe cage" ring. This part also is split. The only other large piece, the base ring, is a rigid non-split steel casting assembled semi-permanently with the generator bracket and contributing substantially to its strength and stiffness. The ring projects downward through and is supported by the bottom web of the bracket, by means of a flanged joint, gasketed for oil-tightness.

Each shoe is carried by a large tool-steel disk which in turn is supported on a thrust pin. It is at this contact point that the characteristic shoe-tilting takes place. Like most pivoted segment bearings previously installed in large American hydro-units, each shoe is carried by a large adjusting screw. Two thrust pins are interposed end to end between the shoe-support and the screw itself. The adjusting screws with their heads projecting in the clear beneath the thrust bracket, are almost down to the level of the Kaplan servo-motor coupling and hence easily accessible for adjustment at any time by removing the oil-tight caps shown. These caps have flats fitting the screw heads and are so designed as to serve as locks to preserve adjustment. This facility of adjustment without draining the oil bath is one feature of novelty on these bearings.

Another improvement giving added accessibility lies in the "shoe cage" above described. It is split at right angles to the two main bracket beams between which the bearing is placed. These beams form the two long sides of the rectangular oil pot. The closing sides are formed by two cross webs each having a door large enough to pass a shoe-cage half, complete with its four shoes and a runner half. Fig. 1 shows such a sub-assembly detached from the base ring and slid to one side. The parts are so designed that when the rotor weight is taken by jacks the shoe supports will slide off or on the thrust pins readily. A special buggy is provided which can be rolled against the oil pot door and receive the sub-assembly. The loaded buggy can then be dragged out clear of the unit. (The wooden structure shown in these figures was placed merely to represent the floor of the generator oil pot.)

Fig. 2 shows the long runner dowels which remain properly entered even if the generator shaft is lifted several inches to get at the Kaplan servo-motor.

In the foreground of Fig. 1 appears a cast shelf adapted to bolt on the side of the bearing. A shoe can be slid out on this ledge for inspection.

Five or ten years ago it was a common practise to build insulation directly into hydroelectric thrust bearings. Recently however, the tendency has often been to place full reliance on the insulation provided elsewhere in the generators. These bearings therefore were built without any insulation of their own.

To summarize, the novelty of this design consists mainly in the ease of vertical adjustment at any time, and the minimum disturbance of other parts of the unit incidental to inspecting or changing the bearing surfaces.

**Carroll F. Merriam:** In many respects the governing system at Safe Harbor represents a distinct advance in power plant design.

Contrary to former practise, the operation of the turbines has been concentrated on a single floor by the location of the pumps and actuators on the same level. This means a saving in personnel as well as avoiding the necessity of men tending pumps located below the main floor. The omission of half of a floor on the level with the top of the generators allows all of the governing equipment to be served by the main cranes, the accumulator tanks being reached through removable sections.

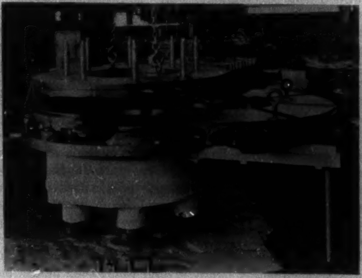

Fig. 2

An important feature is the compromise between the older central pumping plant and the later plan of separate complete governing systems for each unit. The twin system is really a central system for each group of two units, but because the whole can be located in the space between the two units of each pair, no long lines of piping are required. At the same time the interconnection between governors makes a considerable saving in spare pumping capacity that would be required in the unit system to prevent failure of a pump from crippling its turbine.

The pumps have been constructed on a special design to allow the oil to be brought to and taken from each pump through its base in order that quick replacement can be made simply by removing the anchor bolts which serve at the same time as flange bolts, and breaking the shaft coupling. On account of the readiness with which one pump can be interchanged with another, the requirements for spare capacity were again greatly reduced.

As far as possible, the length of the oil lines was held to a minimum particularly for the portions connecting the actuator with the accumulator tanks, the servo-motor cylinders, and the sump tank. The flow in these sections is intermittent with the movement of the gates, and so the inertia of the oil is a detriment to the quick response. The sump tanks were located directly under the pumps by taking advantage of the recess between the scroll cases. Consequently the suction lines are short, giving little friction loss to increase the lift, and the tanks are out of the way and do not occupy valuable space.

The fly-balls are motor-driven from the slip rings of the pilot exciter, and care has been taken to have little weight in the revolving parts in proportion to the power of the motor so that the speed response will be as prompt as possible.

From the electrical point of view, the protective devices, together with the annunciator system, are interesting. The general plan is that emergencies that may arise are divided into two classes, those requiring complete shut-down, and those requiring simply closing the gates to speed no-load position. Impulses received from the respective relays not only indicate the source of trouble, but also act upon one of the two safety devices arranged to produce the desired effect on the governor. The governor motor must be supplied with three-phase current with sufficient voltage to assure its starting before the gates can be opened beyond speed no-load position, except that provision is made that in case the break-away point at which the wheel starts to turn is higher, the gates may be opened but only when the operator is holding a special handle. In case of failure of one phase while the machine is running, the unit would not be shut down.

An interesting feature of the actuator itself is that provision has been made in the design for the eventual installation of several contemplated modifications after sufficient operating experience has been acquired to judge better regarding their desirability. In this respect there are interesting possibilities of improvement by simple substitution of a few special parts in place of the standard equipment.

**R. L. Thomas:** Characteristic features of large hydroelectric developments are their long incubation periods and the prolonged efforts expended in getting them started. Safe Harbor is no exception in this respect, but the project is perhaps unique in that long before it reached the actual development stage it fell into the hands of a strong operating company. Many of the flowage rights required for the development date back to 1902 when they were acquired by an individual, probably as a speculation. After changing hands several times they finally passed into the ownership of the Pennsylvania Water & Power Company, which was organized by Mr. J. E. Aldred, receiver of the McCall Ferry Power Company, which failed in 1907. The McCall Company had originally acquired some of the flowage rights above Safe Harbor for use by the Holtwood (formerly called the McCall Ferry) development, but in the final plans the crest of the Holtwood dam was lowered 20 feet. This left available for another development a fall of 55 to 57 feet from Columbia down to the Holtwood pond.

The Pennsylvania Water & Power Company from time to time, without any publicity and through its regular operating staff, made engineering and economic studies of the upper developments, the first preliminary design and cost estimates having been made in 1916. Additional key properties were also acquired through agents as particularly favorable opportunities arose. No outside services of any sort were employed prior to the making of core borings at the dam site and every effort was made to avoid any publicity. These methods resulted in relatively low costs of property and flowage rights and particularly of preliminary engineering and organization work. The prelicense cost of the Safe Harbor development, exclusive of property, amounts to less than 1 per cent of the total cost of the initial project. Other advantages of the Safe Harbor project are the small cost of railroad relocation work as compared with other developments on the lower Susquehanna, and the small amount of highway and bridge construction or reconstruction required.

The earliest engineering studies were for a dam located about one and one-half miles above the present site. At this location the river is narrower and the dam would have been shorter with considerably less volume of concrete. However, in order to utilize the fall of ten or twelve feet between the upper location and the Holtwood pool, it would have been necessary either to have carried out very extensive tailrace excavation at the upper development, or to have increased the height of the Holtwood dam by means of superimposed gates or movable dam. Furthermore there was no space available at the upper location for construction plant, camp, storage, etc. Exhaustive comparisons of several locations resulted in placing the dam just above the mouth of Conestoga Creek where the Safe Harbor turbines in effect discharge into the upper end of the Holtwood pool. The backwater effect in the Safe Harbor tail-bay varies roughly from one up to several feet, depending upon conditions of river flow, plant discharge and Holtwood flashboard installation.

It is now generally recognized that such "lapping" of heads is the economic method of developing water power sites in series on the same stream. Advantages are the reduction to a minimum of loss in head between plants; increase in amount of storage; and at least partial compensation for loss of head at the lower power house, in case of draw down of the lower pond, by gain in head at the upper plant by reason of the lowering of the tailwater.

**N. B. Higgins:** Mr. Baker's question respecting the omission of superstructure has been the subject of considerable discussion among hydroelectric power plant designers for a number of years. The reduction in cost that may have been effected through the omission of the superstructure was carefully studied before arriving at a decision. A number of factors were given consideration, which cannot easily be evaluated in money; such as, convenience of operation; delay, expense, and loss of service value due to adverse weather conditions; etc. The decision against the outdoor type of construction was not based on costs alone, but on careful consideration of all the factors involved.

A study of the power house cross-section, Fig. 6, will bring out some of the above points. The upstream wall is used for the low tension bus room, transformer pockets, control room, and station service bus room. The roof supports the lightning arresters, and, in part, the transmission line take-off structures. The enclosed generator room made it possible to carry on the installation of all units under cover at the same time. Without the superstructure, considerably more time would have been required for equipment installation (the first generator went into service 67 days after erection was started), with an appreciable expenditure for temporary housing. Some saving in first cost could have been shown, but when all factors were considered, the decision was in favor of enclosing the generator room. There is no doubt that other types of developments may justify the omission of the power house superstructure.

Mr. Hull has raised several interesting questions of design, to which the author replies as follows:

*Transmission System Voltage Control.* The transformer banks at Safe Harbor, supplying the 230-kv and 69-kv systems, are fed from the same 13.8-kv bus system. Busses are tied, or split, according to the system requirements. The connections are sufficiently flexible to permit operation of the 69-kv system in two sections, if necessary.

At times of system parallel operation, variations in the 69-kv transmission system voltage are met by tap changing under load on the 69-kv transformers at Safe Harbor and Holtwood; voltage control on the 230-kv system is obtained by the use of tap changing under load equipment on the 230-kv transformers at Westport, and by synchronous equipment.

The Safe Harbor generator voltage is normally operated at a relatively constant value; line drop compensation is not provided.

*Service Space Requirements.* Space requirements for general service rooms are unusually large, as it is expected that Safe Harbor will become the hub of an extended transmission line system of varying voltages and frequencies. Immediately adjoining the power house, there will be a substation for (ultimately) four 230-kv and six 69-kv, 60-cycle outgoing transmission lines, outdoor 60-cycle—25-cycle frequency changers, and a large 25-cycle, single-phase substation. The large number of transformers, oil circuit breakers, and related equipment thus depending upon power house facilities for assembly and maintenance, made it necessary to provide ample space for this purpose. There are included in this space, power house auxiliaries, water filtration plant, oil filtration plant and storage, boiler room, storeroom, shops, and operating, testing, and engineering offices.

*Transformer Cooling.* Both self-cooled and water-cooled transformers are employed in our Holtwood station. We have found the self-cooled transformers very much superior from the standpoint of maintenance and operation. Considerable difficulty has been experienced with the cooling coils in the Holtwood water-cooled units, on account of the suspended matter in the Susquehanna river water and the acid condition of this water at certain periods. At Holtwood it has been necessary to replace the cooling coils in practically every water-cooled transformer; there has been, also, one transformer breakdown and fire attributable entirely to failure of the water-cooling system.

At Safe Harbor, it would have been necessary to have installed an elaborate pumping and distribution system to handle the cooling water to the transformers as they are located above the forebay level.

For a number of years, water-cooled transformers were favored for hydroelectric stations on account of their relatively lower cost; this was obtained at the expense of lower efficiencies. An economic study comparing water-cooled, self-cooled, and self-cooled forced air transformers, with practically equal efficiencies, showed that in this installation the self-cooled forced air transformers offered the best possibilities.

With our present system of connections, *i. e.*, transformer-line unit, it is essential that each transformer bank have a heavy overload rating, so that the load can be picked up on one line with the other line out of service. The oil insulated forced air transformer is ideal for this purpose, giving high efficiencies at normal load, combined with high overload capacity, at low increase in cost for peak service.

*Use of "Overhung" Generator.* Lower cost and operating advantages led to the adoption of the overhung type of generator. The problem of bearing lubrication is very much simplified in the overhung rotor design, since there is but one guide bearing and this is contained in the same oil housing as the thrust bearing. It is believed that accessibility on this type of machine, with its direct-connected main and pilot exciters, and Kaplan head, is superior to an arrangement with the thrust bearing located above the rotor.

Special attention was paid to bearing layout in the design of the machines. On two of the machines, access to the bearing is at generator floor, through the cooler housings. On the other two machines, access is through the generator pit.

Eight of the units at Holtwood have their thrust bearings below the rotor. In eighteen years of operation, there has been but one failure, and that was due to an operator's error.

The height of the power house is based upon 25-cycle, single-phase generators to be installed in the future, and, is, therefore, more than necessary for the 60-cycle, three-phase generators. Preliminary designs of the manufacturers indicated that from 6 to 8 ft of headroom could be gained by placing the thrust bearing below the rotor with either type of generator.

*Pilot Exciter Supply for Governor Flyball Motors.* It is recognized that in several cases where the pilot exciter has been employed to furnish energy to the governor flyball motors, operation of the high speed excitation system produced phase shift and distortion of the main pole flux. This has caused the governor flyball motor to jump, and the governor system to surge. We believe that this source of trouble has been eliminated by using pilot exciters of ample size, and with compensating windings designed to offset the field distortion and phase shift.

*Use of Higher Generator Voltage.* The use of two separate low voltage windings on the 230-kv transformer banks was considered in the preliminary designs, but this would not have affected the ampere rating of the switches finally adopted, since two breakers would still have been required. We, also, studied thoroughly the use of 26,000 volts for generator voltage. This study indicated that the reduction in bus and switch gear cost was more than offset by the increase in cost, and decrease in efficiency of the generating equipment.

*Water Ring Fire Protection.* Inasmuch as water connections were readily available, it was decided to install water protection as a back-up to the $CO_2$ system, particularly when heat is being bled from louvers in the cooler housings to warm the generator room. In the first few months of operation, before the $CO_2$ system was completed, water was the only method of protection.

*Expansion of Bus.* The method described by Mr. Hull is employed at Safe Harbor for fastening bus copper to the insulators. The bus is clamped tightly at the center insulator, and the other insulators between expansion joints are given a clearance of a few thousandths; this permits the copper to slide, but at the same time is sufficiently tight to enable the bus to withstand mechanical stresses.

*Electrical Bay Ventilation.* There is equipment installed to ventilate the entire electrical bay, including the oil switch rooms, to eliminate condensation, for the removal of heat, and for the removal of smoke and gases in case of fire or electrical failure. The air circulated through the electrical bay is taken from the generator room through a set of forced draft fans, distributed into the oil switch rooms and bus rooms through a system of ducts, and exhausted by a set of induced draft fans. The capacity of the fans is such that for normal ventilation, six air changes per hour will take place in each room. In case of an emergency, such as a fire or electrical failure, the fans may be operated at double normal speed, and the smoke and gases may be quickly exhausted.

*Auxiliary Service Voltage.* In hydroelectric stations, a large number of the auxiliary motors are relatively small, and these are usually driven at an intermediate voltage of the order of 550, 440, or 220 volts. We do not believe, therefore, that 2,300 volts, with intermediate transformers, is justifiable, unless there is a number of large motors, such as motor-driven exciters, involved, or unless the structures are considerably scattered and very long feeders are required. We, therefore, selected 460 volts rather than 2,300 volts, or a combination of 2,300 and 460 volts, because of the reduction in space and operating advantages obtained by the elimination of oil-filled switching equipment and its replacement by air circuit breakers and standard industrial control.

Maintenance of air insulated equipment is more simple, and inspection considerably simplified and made more positive. Intermediate transformers were eliminated.

We doubt that a more reliable service is obtained at 2,300 volts on account of the reduction of short circuits. The protective devices employed at 460 volts are simple, positive, and in each case, we believe, adequate for the duty involved.

It is true that less copper is required for 2,300-volt distribution, but in a system where there is little utilization direct at this voltage, we believe that this advantage is offset by the additional stepdown transformers and equipment required for reduction to the intermediate voltage, and by the fact that considerable distribution is still required at 460 volts.

*Ground Resistance.* The ground system at Safe Harbor as measured at the time the station was placed in service was less than one-half ohm. It is expected that this value will decrease further with the accumulation of silt back of the dam.

# Reception and Distribution of Safe Harbor Energy in Baltimore

BY A. S. LOIZEAUX*

Fellow, A.I.E.E.

***Synopsis.***—*This paper describes how the energy from the new Safe Harbor line is received in Baltimore and how it fits into the total energy supply of steam and hydro.*

*Safe Harbor energy being 60 cycles required a change in frequency from 62½ cycles and is tied in to the 25-cycle system by a 30,000-kw. frequency changer, the characteristics and control of which are described.*

*A bank of surge-proof transformers of 126,000-kva. capacity steps down Safe Harbor energy to 33 kv., handled in a new outdoor substation. This 33-kv. system ties in to both Westport and Gould St. generating stations and through them to the transmission system to Baltimore substations and surrounding territory.*

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PREVIOUS to 1910 the electrical demands in Baltimore were supplied entirely by steam generated energy. The first hydro energy received in Baltimore came from the Holtwood Hydro Generating Station on the Susquehanna River, the first generator beginning service in October, 1910. In 1911, four more generators began operation and by December 1914, eight 25-cycle generators were in service.

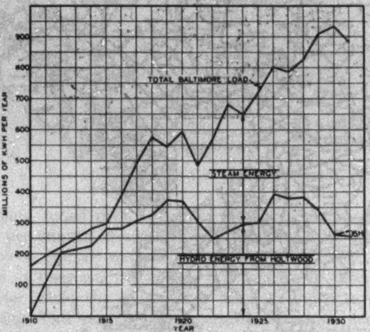

FIG. 1—USE OF HYDRO ENERGY FROM HOLTWOOD IN BALTIMORE SYSTEM

Fig. 1 shows the growth of total load in Baltimore since 1910 and also the hydro energy from Holtwood used in Baltimore. The curve indicates that Holtwood hydro was fully absorbed about the year 1919. Since that year hydro energy has been limited by the amount available, which in turn was governed by river flow and to a lesser extent by the amount of energy sold in Pennsylvania.

Energy from Safe Harbor was first received in December, 1931, and at once took an important place in the energy supply to Baltimore. Fig. 2 shows the amount of hydro energy received from Safe Harbor in the first six months of operation. The Holtwood hydro is superimposed over Safe Harbor hydro and the Baltimore steam makes up the total load. During the years to come, the Safe Harbor energy will doubtless be fully absorbed by the growth of load.

## STEAM AND HYDRO GENERATING CAPACITY

Table I gives the installed steam generating capacity in Baltimore and the installed hydro capacity in Holtwood and Safe Harbor and approximate capacity available in Baltimore.

TABLE I

| | Installed capacity (kw.) | | Approx. capacity available in Baltimore steam and hydro (25 and 60 cycles) |
|---|---|---|---|
| | 25 cycles | 60 cycles | |
| Westport (Steam) | 125,000 | 40,000 | 145,000 |
| Pratt St. (Steam) | 20,000 | | Reserve |
| Gould St. (Steam) | | 72,000 | 72,000 |
| Total Balto. (Steam) | 145,000 | 112,000 | 217,000 |
| Holtwood Hydro | 87,000 | 24,000 | 70,000 |
| Holtwood (Steam) | | 20,000 | |
| Safe Harbor Hydro (4 units) | | 112,000 | 108,000 |
| Total hydro | | | 178,000 |

## ELECTRIC LOAD IN BALTIMORE

The territory supplied by the Baltimore system is indicated by the map, Fig. 3. The northern boundary is the Pennsylvania line; eastern boundary the Susquehanna River and Chesapeake Bay; and the western boundary the two lines indicated. This area has a maximum breadth from east to west of about 50 miles and a maximum length from north to south of about 70 miles.

Baltimore has both 25- and 60-cycle loads; the maximum 25-cycle load recorded being 125,400 kw., the maximum 60-cycle load being 104,800 kw., and the maximum simultaneous load on both frequencies being 188,200 kw.

Twenty-five cycle frequency was originally chosen for industrial purposes and for the operation of rotary converters. Growth on this frequency has been held back in recent years in favor of the 60-cycle system.

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*Consolidated Gas Electric Light and Power Company of Baltimore.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

### CHANGE OF FREQUENCY

Safe Harbor energy was first received in Baltimore on December 12, 1931, at a frequency of 62½ cycles to conform with the Baltimore system. On December 27 this frequency was changed to flat 60 cycles, at which time the older frequency changers were shut down. The sole 25- to 60-cycle frequency changer now operating is located at Westport and is capable of generating 30,000 kw. of either frequency. The old frequency of 62½ cycles was originally chosen to take advantage of the simple ratio of 4 and 10 poles on the 25 and 62½ cycle machines, the cost of such sets naturally being lower than sets with 10 and 24 poles respectively, as required by 25 to 60-cycle frequency.

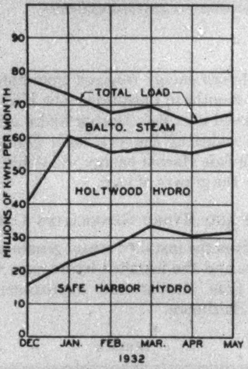

FIG. 2—SYSTEM OPERATION—HYDRO AND STEAM

### FREQUENCY CHANGER

Fig. 4 shows the load carried by the frequency changer for the first six months. The 60-cycle generation is plotted upward from the zero line and the 25-cycle generation downward from the same line, the ordinates between the two curves giving a total output in both directions which has amounted to about 8,000,000 kw-hr. per month. This machine forms a flexible tie between the 25- and 60-cycle systems enabling them to be run to some extent as a single system.

In view of the importance of this frequency changer in the operation of the Baltimore system it may be of interest to mention some of the characteristics of the machine and its control. The machine itself is shown in Fig. 5.

### POWER-FACTOR CORRECTION AND CONTROL

The 60-cycle generator has a full load capacity of 30,000 kva. at zero per cent power factor and the 25-cycle generator a capacity of 30,000 kva. at 70 per cent power factor. These capacities enable the machine to provide a substantial correction to power factor as may be needed on each system. The 25-cycle system carrying many rotary converters does not need as much correction as the 60-cycle system.

The desired voltage control of the set is obtained by the use of a separate exciter for each generator and a pilot exciter for each main exciter. A voltage regulator is supplied on the 60-cycle machine to provide for quick response regulation of the 60-cycle generator voltage. In addition to the regulator a so-called watt balance relay has been installed on both the 25-cycle and 60-cycle machines. The main purpose of these watt balance relays is to provide a means for automatically increasing the excitation upon the application of a heavy load to the frequency changer in order to increase the pull-out torque. The pull-out torque at rated voltage and full excitation is 62,500 kw. or over twice the normal rating of the machine. The main generator circuits are provided with oil circuit breakers but so relayed that they will open automatically only in the event of trouble within the machine windings. Otherwise they will remain closed to hold the 25- and 60-cycle systems together.

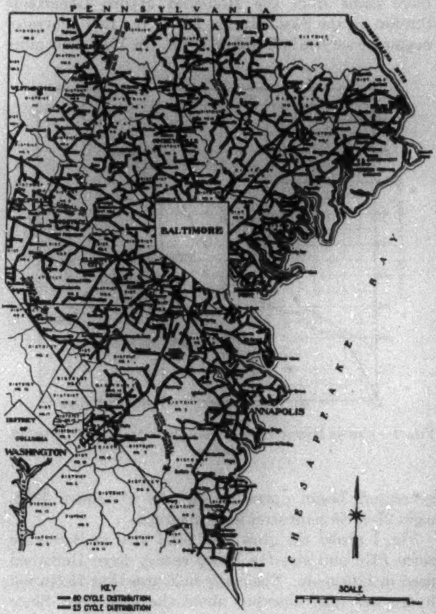

FIG. 3—ELECTRICAL DISTRIBUTION

Consolidated Gas Electric Light and Power Company of Baltimore and Annapolis and Chesapeake Bay Company

The full load efficiency of this set is 96.15 per cent and at ½ load 95.25 per cent. The resultant losses are less than one-third of the aggregate losses of the old frequency changers formerly operating in the substations. The saving in losses alone in the first five months of 1932 during operation of this single machine being 6,681,500 kw-hr.

### MECHANICAL FEATURES

Both generators of the set are equipped with closed air circulation and each machine has two surface type coolers, tubed with Admiralty metal: 60,000 cu. ft. of air per minute circulate through each machine and its coolers. Harbor water is circulated through the tubes and as there are two coolers it is feasible to clean one cooler while the machine is running under reduced rating. This set has been operating about six months at this writing, from the inauguration of Safe Harbor service and has not been shut down during this time. The coolers are located in the foundation under the end-bells of each machine, making a compact and inconspicuous layout. On the 60-cycle machine a frame shifter is installed on the center line of the stator and between the coolers. This is operated by a motor driving worm and gear with links connecting to the stator. The operation of the set has been exceptionally smooth and there is comparatively little noise because of the enclosed construction.

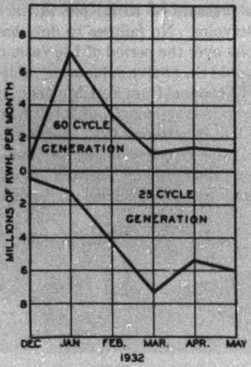

FIG. 4—FREQUENCY CHANGER OPERATION

### ENGINEERING STUDIES PRELIMINARY TO THE RECEPTION OF SAFE HARBOR ENERGY

In making plans for the reception of Safe Harbor energy in Baltimore, it was necessary to make engineering studies, some of which were made in cooperation with the Pennsylvania Water and Power Co. Some of the more important of these studies are as follows:

The voltage of transmission to Baltimore.

The stability of the transmission system.

The location of terminal stations in Baltimore.

The kind and type of transformers used to step down.

The step-down voltage and intermediate transmission system.

The rearrangement of the Baltimore 13-kv. distribution cable system and the voltage regulation of the same.

The results of these studies are indicated by the equipment chosen as described in this paper, each decision arrived at being, as a rule, the result of a number of studies to determine the most economical, reliable, and otherwise satisfactory system and equipment.

### TRANSMISSION FROM SAFE HARBOR TO BALTIMORE

This subject is fully covered in Mr. Hansson's paper submitted at this session. Suffice it to say that two transmission lines were decided upon; one terminating at Westport, our largest power station and center of distribution, and a second future line to terminate at Riverside, a property reserved for a future steam generating station. The transmission voltage of 230 kv. was found to give the necessary capacity with small line drop and also to give the greatest dependability by being as nearly as possible lightning-proof. The stability of this line proved, under mathematical analysis, to be entirely satisfactory. The 230-kv. potential was also best suited to possible future interconnection with other systems.

FIG. 5

### BALTIMORE TRANSMISSION AND DISTRIBUTION SYSTEM

Fig. 6 is a single-line diagram indicating the main connections of the 60-cycle transmission and distribution systems. The present Safe Harbor line reaches Baltimore at Westport, at the west end of the system, and the future line will reach Baltimore at Riverside at the east end of the system. A large part of the energy stepped down at Westport is distributed through 13-kv. underground cables to various substations. It was necessary further to determine whether to step the Safe Harbor power down to 13 kv. directly or to use an intermediate bus of 33 kv. The latter plan was decided upon because the 33 kv. was more economical to transmit large blocks of power to the Gould St. Station, and in the future to the Riverside Generating Station and terminal of the second Safe Harbor transmission line. To step down directly to 13 kv. would also have overtaxed the capacity of the 13-kv. switches in our power stations, whereas by the use of an intermediate voltage and transformers the excessive concentration of power at 13 kv. has been avoided.

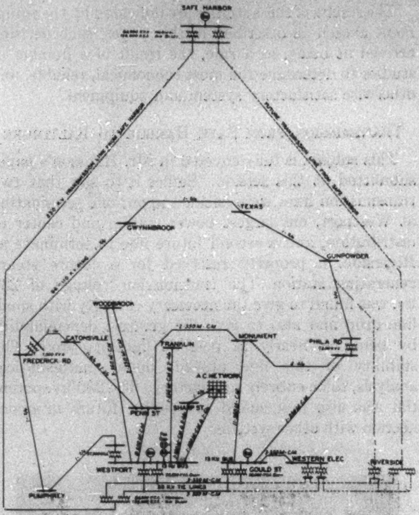
SAFE HARBOR
230 K.V. TRANSMISSION LINE FROM SAFE HARBOR
FUTURE TRANSMISSION LINE FROM SAFE HARBOR
TEXAS
GWYNNBROOK
GUNPOWDER
WOODBROOK
CATONSVILLE
FREDERICK RD
FRANKLIN
MONUMENT
PHILA RD
A.C. NETWORK
PENN ST
SHARP ST
WESTPORT
GOULD ST
WESTERN ELEC
RIVERSIDE
PUMPHREY
33 KV TIE LINES
13 KV BUS

Fig. 6—60-Cycle Transmission System Baltimore and Vicinity

## Substation Connections

Fig. 7 gives a single-line diagram of the incoming line, step-down transformers and 33-kv. station. The secondary side of the transformer bank is controlled through two sets of buses at 33 kv. and delivers energy through four heavy connections of 36,000-kva. capacity each.

## 33-Kv. Ties Between Generating Stations

From the 33-kv. step-down station, shown on the diagram, two 36,000-kva. transmission ties are taken through oil-filled reactors and extend about 7,300 ft. to Gould St. About 2,240 ft. of this distance is a submarine section which crosses the Spring Gardens arm of the harbor near Westport.

Each tie consists of three 3-conductor cables of the shielded type with no belt insulation. The conductors are 350,000 cir. mils sector shaped insulated on the land cables with 26/64 in. paper and in the submarine section with 28/64 in. paper. The sheath is 5/32 in. lead and the submarine section is armored with No. 4 galvanized steel wire. The dielectric loss measured at the factory was 0.09 watts per foot in the three-phase cable when operating at rated voltage and at maximum safe operating temperature of 71 deg. cent. The power factor of the charging current was 7/10ths of one per cent.

The normal capacity of each cable is 12,000 kva. at 33 kv. or 36,000 kva. per tie circuit.

A General Electric oil reservoir is supplied at each joint and a pressure of 15 lb. per sq. in. maintained in these reservoirs. No failures to date have occurred in these cables over the period of 1½ years of service.

East of Gould St. twelve submarine cables have been laid across the channel from Fort McHenry to Lazaretto Point, with an average length of 2,130 ft. each. These cables were laid in a trench 47 ft. below mean low tide and covered with five feet of fill for protection. Only three of these cables are now operated for carrying load, but the remainder are designed to form a future tie from Gould St. through to the Riverside Station and second Safe Harbor line.

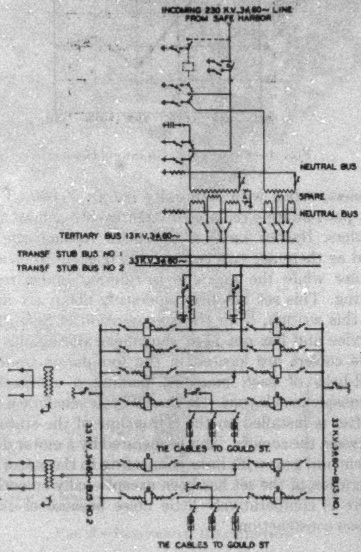
INCOMING 230 K.V. 3φ 60~ LINE FROM SAFE HARBOR
NEUTRAL BUS
SPARE
NEUTRAL BUS
TERTIARY BUS 13 K.V. 3φ 60~
TRANSF STUB BUS NO 1
TRANSF STUB BUS NO 2
33 K.V. 3φ 60~
13 K.V. CABLES TO WESTPORT SWITCH HOUSE
33 K.V. 3φ 60~ BUS NO 2
33 K.V. 3φ 60~ BUS NO 1
TIE CABLES TO GOULD ST.
TIE CABLES TO GOULD ST

Fig. 7—Westport 230-Kv.—33-Kv. Substation

At Gould St. 33-kv. energy is stepped down to 13 kv. in two transformer banks shown in Fig. 8. These are auto transformers, three-phase, self-cooled, conservator type, 36,000 kva. each. They are equipped with tap changers to operate while carrying load, these tap changers being mounted in the box seen on the upper part of the transformer case. These transformers have a reactance of approximately 4 per cent.

### CABLE REACTORS

In Fig. 8 also, are seen the six cable reactors installed on the six 33-kv. tie cables from Westport. These reactors have a rating each of 456 kva., three-phase, at 60 cycles, 225 amperes per phase, 675-volt reactive drop, 55 deg. cent rise, for use on 34.5-kv. circuits. On this basis each coil will have a 3.38 per cent impedance drop at full load. This reactance is to limit the values of short circuits that may occur on the 33-kv. ties. The short-circuit guarantee of these reactors is 30 times full load for five seconds.

FIG. 8

### TRANSFORMERS CONNECTING TO WESTPORT SWITCH HOUSE

Two 36,000-kva. tie transformers similar to those described at Gould St. tie between the 33-kv. system and the 13-kv. Westport Switch House. The transformers are built with the necessary reactance to limit short-circuit current, while the cables to Gould St. are provided with special oil filled reactors. These four feeders total 144,000 kw. combined capacity which is sufficient to transmit the full capacity of the step-down transformers of 126,000 kw.

The Safe Harbor energy transmitted through the tie lines to Gould St. is distributed through 13-kv. cables, as shown in Fig. 6, to Monument St. and Philadelphia Road Substations. The 66-kv. ring around Baltimore is fed from the Westport 13-kv. bus through step-up transformers, as indicated.

### 25-CYCLE SYSTEM

Fig. 9 is a simplified diagram of the 25-cycle system connected, as previously stated, to the 60-cycle system through the 30,000-kva. frequency changer.

### STEP-DOWN SUBSTATION AT WESTPORT

Fig. 10 gives a general view of this station, showing railroad tracks in the foreground with siding to the transformer assembly house at the left. The incoming line from Safe Harbor is in the left center. This view also shows the oil storage tanks and oil filter house close by, with the four large transformers and the control house. Fig. 11 is a close-up of the 220-kv., 42,000-kva. transformers showing radiators with individual blowers. The rectangular metal tank on the side of each transformer contains switches and equipment for tap changing under load.

### MAIN TRANSFORMERS

The main transformer bank consists of four single-phase, 60-cycle, 28,000-kva., self-cooled shell type transformers, one of them being a spare unit. The radiators on each transformer are provided with small blowers which give an overload capacity of 50 per cent, or 42,000 kva. This air blast is controlled automatically from the transformer oil temperature and operated by mercoid switches which start and stop the fans automatically as required by the operating temperature. The spare transformer is connected so that it can be quickly switched in to replace any transformer that it is desired to disconnect. This operation takes from 8 to 10 minutes.

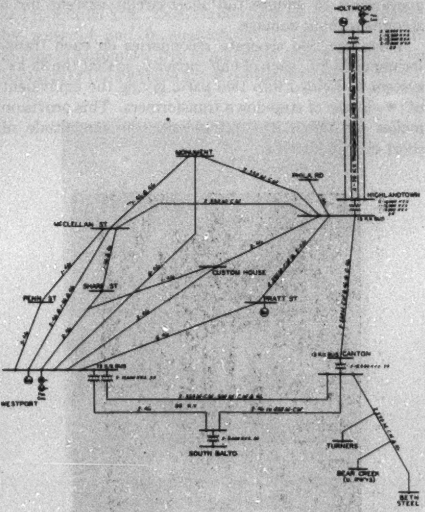

FIG. 9—25-CYCLE TRANSMISSION SYSTEM BALTIMORE AND VICINITY

Each transformer is provided with tap changers for operation under load so that the voltage of the system may be smoothly maintained over all load conditions. These taps are on the 230-kv. winding adjacent to the neutral point giving a voltage range of 20 per cent.

Each transformer has a tertiary winding, 9,800 kva. at 13,800 volts, delta connected. This winding aids in the stabilization of the system neutral and suppression of third harmonic voltages. The transformers are guaranteed to endure full short-circuit current for 5 seconds without damage.

Fig. 10

There are two separate secondaries on each transformer of 33 kv., each of half capacity, so that the 33-kv. system is divided into two parts giving the equivalent of two banks of step-down transformers. This provision makes for reliability and reduces the magnitude of short-circuit currents.

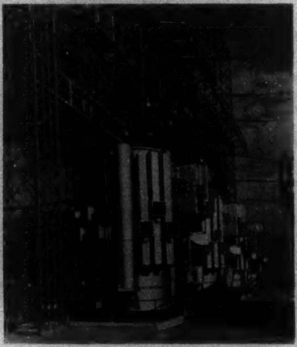

Fig. 11

Transformers are connected star-star with solidly grounded neutral. Transformers are supplied with condenser bushings including a potential device which operates neon lights and relays. Differential protection is provided for each of the three windings of each transformer so that failure in a winding will cause the transformer bank to be promptly cut out by automatic switch operation on the 33-kv. side. The 230-kv. side would be cleared by the overload tripping of switches at Safe Harbor.

These transformers were too large to ship completely assembled or to ship in oil. It was necessary to provide a transformer assembly house, shown in Fig. 12, equipped with a two motor lifting crane of 75 tons rated capacity. The transformer windings were shipped sealed in nitrogen to protect them from moisture. During assembly a blast of heated air was provided through the 6-in. gate at the bottom and when assembly was completed oil from tank cars was passed through a conditioning and drying machine into the transformer tank. Each transformer was moved from the transformer house over a wide gage track to a transfer car, shown in Fig. 13, which moves the transformer to its permanent berth. By this method any transformer can be promptly moved to the transformer assembly house where it can be opened, dismantled, or shipped.

Fig. 12

The transformers are protected by the inertaire system to eliminate oxygen and moisture from the space above the oil.

### Surge-Proof Construction of Transformers

Much has been written concerning the surge-proof design of these transformers which were the first very large transformers to which this design was applied. The two outstanding features of the design are first, the proportioning of the high-tension coils to distribute electrostatic strain evenly over the winding and second, the boxing of each coil in insulation to eliminate creepage surface. It is unnecessary to repeat here what has appeared in the technical press. It is hoped that they are practically immune to lightning damage, having been subjected to an impulse voltage surge, on test, of 3 million volts without damage.

### Ground System

A ground system is provided consisting of a network of 1 million and 500,000-cir. mil stranded copper cables laid 3 ft. deep in the ground over the entire area of the 220-kv. and 33-kv. substations. Ninety-five ground rods have been provided driven 12 ft. deep. Connections between cables and rods are brazed to provide permanent low resistance connections. All steelwork, transformer tanks, switch tanks and metal structures are grounded to this network system.

### OIL STORAGE AND PUMPING

Two tanks are provided each holding 21,000 gallons—one for clean and one for dirty oil. These tanks are enameled inside to prevent contamination of the oil.

FIG. 13

In the oil house close by are provided pumps and a large capacity conditioning machine which filters and dries oil by a vacuum process and an auxiliary blotter process. Any transformer can be drained and filled while in its permanent location, the oil being handled through the equipment described

### LIGHTNING ARRESTERS

Lightning arresters, shown in Fig. 14, are of the autovalve porous block type and are provided to relieve surges on the line. The upper part or gap section of the arrester is suspended from overhead steelwork through suitable insulators, the line connects to the top of the arrester, the upper section consisting of sphere gaps and the lower section of porous block elements. The normal rating of the arrester is 200 kv. but there is an additional section of elements normally short-circuited by a switch. If 25 per cent overvoltage occurs on the 33-kv. bus, this switch is opened, cutting in the additional elements and giving the arrester a rating of 240 kv. The purpose of this automatic device is to prevent discharge of the arrester in the event of overspeeding of the hydro generators at Safe Harbor.

Spill gaps are provided on each line with a 3-ft. diameter top ring, a 5-ft. diameter bottom ring, and a 64-in. gap to relieve a high-voltage surge in the event that the lightning arrester cannot dissipate the surge. These spill gaps will flash over before the transformer bushing flashes over and the transformer bushing will flash over before the transformer windings are injured.

The various elements of insulation in this station are coordinated, the breakdown strength beginning with the lowest strength as follows:

The lightning arrester, spill gap, transformer bushing, and finally the transformer itself.

The steelwork for both 230-kv. and 33-kv. stations is all galvanized. Disconnecting switches are mounted in direct line of high-voltage connections to transformers and operated from a convenient position on the ground.

The 230-kv. equipment is protected by five ground wires strung well overhead to continue the ground protection given to the transmission line.

### OIL CIRCUIT BREAKERS

No oil circuit breaker is provided on the 230-kv. coming line, although space is left for the same if it should be required when the second line is built from Safe Harbor. All the switching is done on the low side of the large transformer. These switches are rated at 34.5 kv., 1,200 amperes and have a rupturing capacity of 1½ million kva. Each three-phase switch is operated by solenoid and is guaranteed to clear the circuit in case of automatic trip in not more than 8 cycles. The contacts of the switches are of the deion type.

FIG. 14

### CONTROL HOUSE IN OUTDOOR STATION

The Westport Operating Room and Load Dispatcher's Room are about 900 circuit feet distance from the step-down station and this long run would have introduced too great a drop for current transformer circuits and control circuits connected in the usual manner. It would also have cost very much more than the method adopted which was the establishment of a control center in the outdoor station to serve as the terminal point of the secondaries of current and potential transformers and the control wires from oil circuit breakers and other equipment.

The control house contains storage battery and charging set; also switchboards for control switches, relays and meters. The control house forms one of two control points, the other being in the switchboard operating room, so that a dual control is furnished. Electrically operated equipments, such as oil circuit breakers, fans, lightning arresters, switches, etc., are controlled from the switchboard operating room through 16-conductor, No. 16 wire control cables, which operate relays in the control house and these relays close or open the d-c. circuits to the equipment.

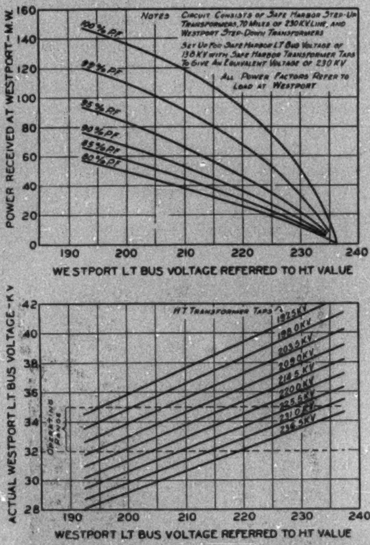

Fig. 15—Voltage Regulator Curves for Safe Harbor—Westport Circuit Used in the Determination of Westport Transformer Taps

The control house also contains standard instruments and meters for measuring the circuit outputs and in the control house are located special relays and totalizing instruments which pass on the principal indications to the switchboard operating room in the power house.

### Voltage Regulation of Baltimore Load

One fundamental requirement of the voltage regulation in Baltimore is to supply the 13-kv. customers with approximately constant voltage. Many of these customers are supplied by radial cables from substations, others by cables from generating stations. The practise has been, and is, to so regulate the 13-kv. buses at the Westport and Gould St. generating stations that the voltage at customers' premises should not vary materially. This means that at times of heavy load the generating station buses carry a higher voltage than at times of low load, the general values ranging from a minimum of 12.8 to a maximum of 14.2 kv. and the actual voltage of these buses at any time being that which will give the best average voltage to 13-kv. customers.

Another requirement of voltage regulation is the supply to the a-c. network in the central part of the city, which network is of recent construction. Our experience to date, indicates that a very uniform network voltage has been maintained by the same method of compensating for drop by increasing voltage at times of heavy load.

The company has a large 4,000-volt distribution load fed by radial feeders from substations. This does not introduce a regulation problem as each three-phase feeder is equipped with three single-phase regulators between phase lead and ground which provide excellent regulation at the feeder point.

To obtain satisfactory and easily controlled voltage it was decided to equip the 230-kv. step-down transformers with tap changing under-load equipment.

Fig. 15 shows a typical sheet of curves that were developed to determine the best ratio for step-down transformers and the proper taps for obtaining desired voltages under all load conditions and varying power factors.

Taking the normal generator voltage at Safe Harbor and taking one of the transformer taps at Safe Harbor the upper curves were laid out with ordinates of power received at Westport. The abscissas were Westport low-tension bus voltages referred to high-tension values in kilovolts. Actual voltage values were then calculated following Nesbit's "Electrical Characteristics of Transmission Circuits" and using Wilkinson's formula and the circle diagram. Such calculations were made for various power factors from 100 to 80 per cent. These curves give the terminal voltage at Westport for any load on the transmission line and any particular power factor. These curves show the regulation of the transmission line including the step-up bank at Safe Harbor and step-down bank at Westport. It is of interest to note the greatly increased amounts of power that can be transmitted at high power factor approaching unity for the same voltage drop.

In order to forecast actual Westport low-tension bus voltages the curves just below are developed with actual voltages as ordinates and the same abscissas as the upper curves. Each of these straight lines represents the conditions under one transformer tap, of which there are nine in all. The satisfactory range of voltage conditions lies between 32 and 35 kv. as indicated by the horizontal dotted lines in the figure.

The taps on the step-down transformers provide as above indicated control of the 33-kv. voltage. In tying from this system to the 13-kv. bus at Westport and at Gould St. generating stations and in the future at Riverside we do so through transformers of 36,000-kva. capacity, which are also provided with tap changers operated under load, which will enable the several generating station voltages to be adjusted as required to suit their individual transmission requirements.

### TESTS OF 230-KV. TRANSMISSION LINE

On completion of the Safe Harbor-Baltimore line and before the first generator was available at Safe Harbor tests were made, in cooperation with the engineers of the Pennsylvania Water and Power Co., from the Baltimore end to determine the electrical constants of the line for the purpose of analyzing and predicting its performance under normal and abnormal conditions. The measured values checked very closely with the calculated or theoretical values. A few of the interesting test results are as follows:

The insulation resistance of the three conductors to ground was in excess of 200 megohms indicating that there were no grounds on the line.

The d-c. resistance of each conductor at 25 deg. cent. was found to be 8.0 ohms. The a-c. 60-cycle resistance per conductor at 25 deg. cent. was found to be 8.7 ohms. The difference between the a-c. and d-c. resistance of 0.7 ohms is due principally to hysteresis and eddy currents or iron losses due to the steel core used in this aluminum conductor.

The d-c. resistance of the earth and ground wire return between Safe Harbor and Baltimore was found to be 0.55 ohms, this indicating a very low value of ground resistance at both ends of the line. The resistance of the two ground wires in parallel is about 16 ohms indicating that in this test very little current passed through the ground wires.

The effective 60-cycle a-c. resistance of the earth and ground wire return was found to be 6.43 ohms. This value is much greater than the d-c. resistance due to the relation of the leakage impedance of the line conductors and ground wires and the mutual impedance of the earth.

The balanced impedance per phase at 25 deg. cent. was found to be 59.7 ohms per conductor.

The zero phase sequence impedance was found to be 125.4 ohms. This value is three times the impedance measured by taking the three conductors in parallel with the return circuit through the earth and overhead ground wires. This value is of real importance in the calculation of ground faults and the solving of inductive coordination, and in figuring the stability of the line under various fault conditions. It is of interest to note that this value is 210.4 per cent of the balanced or so-called positive phase sequence impedance per phase.

The open-circuit line excitation at 60 cycles and 230 kv. required 51.1 amperes or 20,400 kva. This condenser effect is an important element in the control of power factor and line voltage. The high charging kva. of such a transmission line has the well-known result of increasing voltage on the generators for a given field current due to the boosting effect of armature reaction of currents at leading power factor. If the transmission line is excited by a single generator, this condenser effect may lead to excessive line voltages unless the field current is held to the necessary low value. The Safe Harbor generators are designed with this in view but in exciting the line from the Baltimore generators the excitation must be controlled to the desired low value.

# Low-Head Hydroelectric Developments

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Member, A.I.E.E.

***Synopsis.***—*In the last few years very rapid progress has been made abroad in developing the theory of low-head developments and this has resulted in a wider use of Kaplan turbines. Every engineer interested in the design of low-head developments should familiarize himself with at least the principles of this theoretical work and its practical application.*

*The paper gives a general outline of the present situation which seems to have been somewhat neglected in the United States. Starting with general ideas about Francis, propeller, and Kaplan turbines in low-head developments, the important points are discussed with respect to cavitation and pitting, modern design theories, design of propeller and Kaplan turbines and the research requirements and practise. Next the practical application of the theories are demonstrated by a table of designs executed or projected, and finally, some of the tendencies in extending the use of Kaplan turbines for higher and much lower heads are discussed.*

The design of an up-to-date low-head hydro-power plant requires a thorough understanding of the ideas and theories that have originated within the past few years in connection with such developments. The present paper is a continuation of a paper† delivered by the author at the 1930 Summer Convention of the Institute, and reviews the latest theoretical and practical work and discusses the modern trend in the design of low-head plants.

In the eastern part of the States, and to a greater extent in Europe, the number of power sites that can be developed economically by the use of conservative Francis turbines is rapidly diminishing. Many of the remaining low-head sites can be developed only by the use of more economical methods, *i. e.*, by turbines of the propeller and particularly the Kaplan type.

It took about twenty years to develop the mere ideas of Professor Victor Kaplan. This work started with small models of the propeller and Kaplan turbines, followed by commercial sized machines, the first of which, a 40-hp. unit, was put into operation in 1919, and finally in 1930 reached the size of 38,000 hp. in the Ryburg-Schworstadt units, and in 1931 of 42,000 hp. units in the Safe Harbor plant.

In so far as physical size is concerned, the Ryburg-Schworstadt turbines were the largest built, and the year 1930, when these turbines were put into successful operation, can be considered as the turning point. Today, however, Kaplan turbines are under construction, which are even larger in capacity and physical size than the Ryburg-Schworstadt units; this could have been accomplished only by the most efficient collaboration between theory and research and their practical application. The credit for this past accomplishment was due entirely to European engineers, who developed remarkably close cooperation between all interested parties, coupled with an amazing amount of work.

The conditions in the States were unsatisfactory and the turbine manufacturers were unable to make the model tests so essential to the development and proper design of Kaplan and propeller turbines. Consequently, when the Safe Harbor development was undertaken, the operating company had to build and operate its own cavitation laboratory in order to secure the necessary information from model tests.

## Francis, Propeller, and Kaplan Turbines in Low-Head Developments

Large low-head developments require the handling of very large volumes of water. In many cases, neither effective storage nor regulation can be obtained economically. Not only does the amount of available water vary but the turbines must be operated under a varying head and these variations are relatively much larger than in medium or high-head developments. Hence the economy of low-head developments depends on the ability to handle at low cost and at high efficiency these large and varying volumes of water at varying heads.

The convenient criterion for comparing different turbines is the so-called specific speed which represents the number of revolutions per minute that a homologous model runner must make to develop one unit of power at one unit of head. In English units this means a comparison of models that will develop one horse power at one foot of head.

At the same head and output the number of revolutions of different turbines is directly proportional to the ratio of their specific speeds, and for turbines of similar design the diameters of the runners are in inverse proportion to the ratio of the square roots of their specific speeds.

For Francis turbines an increase in specific speed is accompanied by a decrease of efficiency, due to the increased friction and eddy losses.

The original Francis turbines had proper specific speed for medium heads but for low or high heads their specific speeds were unsatisfactory. Consequently, to make such turbines more suitable for such heads, they must be modified to lower the specific speed for high heads and increase it for low heads.

Considering that the amount of space required for a unit, and hence the size of the sub and super-structure,

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†*Present Day Hydro Power Practise in Central Europe*, by A. V. Karpov, A.I.E.E. Trans., Vol. 49, No. 4, p. 1642.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

depends on the diameter of the runner, and also that the size and cost of the generator diminishes rapidly with an increase in specific speed, the important economical influence of the change from lower to higher specific speed runners can be seen clearly. For rough approximations it can be stated that the initial cost of the power-house, including the hydroelectric machinery, for low-head developments, is approximately in inverse ratio to the three halves power of the specific speed.

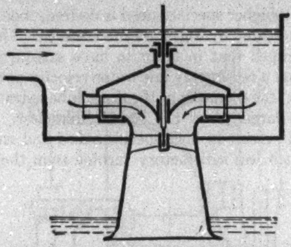

FIG. 1—ORIGINAL FRANCIS TURBINE

In the States, it was realized quite a number of years ago that high specific speed is one of the most important factors in decreasing the cost of a low-head development and since about 1900 the American-designed high specific speed Francis turbines have been generally used, notwithstanding their lower efficiency.

The evolution of the Francis turbine during the last 50 years is indicated by Figs. 1 to 6 inclusive. Fig. 1 shows the original conservative Francis design. The column of water is divided into separate streams and admitted to the runner by means of regulating vanes or wicket gates. The position of the vanes, determined by the governor, depends on the operating conditions and varies from practically closed position at no load to full open position at maximum load. The vanes are shaped and arranged so that at each position of the gates a certain amount of water is admitted, without throttling action and without power losses due to such action. The water streams formed between two adjacent vanes enter the runner at a certain angle, which depends on the position of the gates. In order to insure maximum efficiency, the flow through the turbine should be smooth and without rapid change either in the direction or in the velocity of the individual streams. This is accomplished by the proper combination of the velocity and direction of the streams, flowing from the wicket gates, with the shape of the runner vanes or buckets and the proper number of revolutions of the runner. For each position of the wicket gates a certain shape of the runner buckets and a certain number of revolutions of the runner will give maximum efficiency. Since it is obviously impossible to change the shape of the buckets there is a certain opening of the wicket gates and a certain number of revolutions of the runner that corresponds to the maximum efficiency at a given head. At every other opening of the gates, the efficiency will be lower even if the number of revolutions of the runner could be properly adjusted. In the practical operation, the number of revolutions is held constant; consequently at every opening of the gates, other than the most favorable one, the efficiency will be lowered. The same conditions apply if there is a change in the head for which the turbine is designed. In other words, for each turbine at a given head and given number of revolutions, there is a certain opening of the gates or a certain loading at which the turbine develops its maximum efficiency; under any different head or loading the efficiency will be lower.

In the conservative Francis design shown by Fig. 1, the water, after passing the gates, enters the buckets and the conversion of energy takes part during the time the water flows in horizontal streams through the buckets. After the water leaves the buckets the water streams are deflected and their direction is changed by the deflector. In such a turbine the action of the water is distinctly subdivided as follows:

1. The water is divided into separate streams by the gates and flows at a certain angle toward the runner buckets.
2. The conversion of energy occurs in the buckets.
3. The direction of the water streams is changed and they unite in a single water column entering the draft tube.

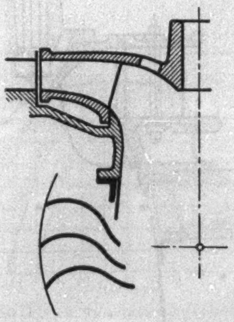

FIG. 2—FRANCIS TURBINE FOR HIGH HEADS

Reduced specific speed

The specific speed of such a turbine may be changed within rather narrow limits by changing the shape of the buckets. If the specific speed is to be changed more radically, then a modification of this design is necessary. If the head is high and it is desired to reduce the specific speed, then the modifications shown by Fig. 2 are made. The change consists principally in increasing the outside diameter of the runner and thus have a smaller number of revolutions, but with the same peripheral speed and hence a lower specific speed. The height of such a runner must be reduced so as to pass the same amount of water and thus have the same discharge. If at the same time the shape of the buckets and particularly the entrance angle is changed, as indicated by the drawing, then a further reduction of specific speed may be made by reducing the velocity of the water entering and leaving the runner. The result will be a turbine with a smaller number of revolutions and lower specific speed than the original Francis design, but of larger physical dimensions.

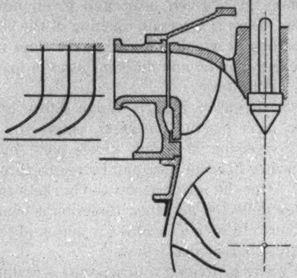

Fig. 3—Francis Turbine for Moderately Low Heads

Higher specific speed

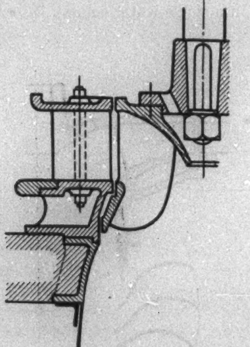

Fig. 4—Francis Turbine for Low Heads

High specific speed

If the head is low and it is desired to increase the specific speed, then the modification indicated by Fig. 3 may be made. The diameter of the runner is decreased and the height of the wicket gates is increased; this increases the specific speed by increasing the number of revolutions so as to retain the same peripheral speed. The change of the shape of the buckets makes possible a still larger increase in specific speed owing to the increase of the water velocity. In such a design the water velocities will be higher and the runner more cramped than the original Francis runner. After the water streams leave the gates the conversion of energy from the water to the runner and the deflection of the direction of the water flow in the individual water streams occur simultaneously, contrary to the original Francis design.

If a still higher specific speed is desired, then the conditions indicated by Fig. 4 are encountered. The runner is so cramped that in order to have satisfactory conditions and a reasonably low water velocity at the draft tube inlet, the diameter of the draft tube entrance must be made larger than the runner diameter. Such a design will result in high specific speed and small size, but a much less satisfactory turbine than the original Francis design. The high water velocities cause high friction losses and even under most favorable loading conditions the efficiency will be comparatively low. For other loadings or for varying heads the cramped conditions and the high water velocities are responsible for the very high eddy losses, which rapidly reduce the efficiency. To reduce the friction losses in such high specific speed turbines, the modification of design indicated by Fig. 5 may be adopted. Here the friction areas are reduced by leaving a free space between the wicket gates and buckets.

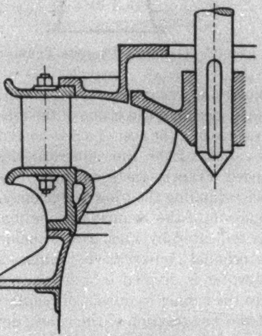

Fig. 5—High Specific Speed Francis Turbine with Reduced Area of Buckets

The final step that can be made in this direction is indicated by Fig. 6, where the runner has no buckets but properly shaped radial partitions.

The design tendency that was developed in an attempt to increase the specific speed and to make Francis turbines better suited to low-head developments was checked and any further increase in specific speed was stopped by: (1) the decrease in efficiency on account of increase in specific speed; (2) the sensitiveness of such turbines to variations in head; or in other words, a rapid decrease in efficiency when operating under heads different from that for which the turbine is designed; and (3) cavitation and resulting destruction of the runner.

The introduction by Kaplan of the propeller turbine changed the situation radically and made it possible to build turbines of much higher specific speeds, which showed high efficiency at the most favorable loading and were much less sensitive to variation in head. Finally, the introduction by Kaplan of propeller turbines with adjustable blades—known as Kaplan turbines—extended the high efficiency of propeller turbines over a wide range. The danger of cavitation limits the present use of propeller and Kaplan turbines to a head which at present is about 100 feet.

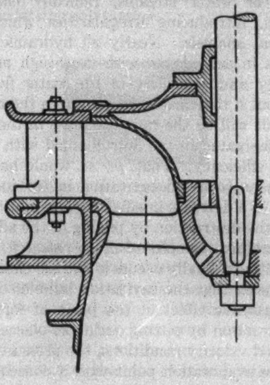

Fig. 6—High Specific Speed Francis Turbine with Radial Partitions

The propeller or Kaplan turbine is somewhat similar to the high-speed Francis turbine shown by Fig. 6, with this important difference, however, that all friction surfaces are reduced as far as possible by substituting for the Francis runner the propeller runner with its small area.

The difference between the Francis, propeller, and Kaplan types of turbines is well illustrated by Fig. 7, which shows the very satisfactory efficiency curve obtainable from a very low-specific speed Francis turbine and the less satisfactory curve for Francis turbines of high specific speed; in this respect, the propeller turbine of still higher specific speed is very much in line with the Francis turbine. Taking finally a properly designed high specific speed propeller turbine and changing it to a Kaplan turbine, with adjustable blades, not only gives a better range of efficiency than the lowest specific speed Francis turbine shown on the diagram, but at the same time results in a turbine that can stand considerable overloading and yet retain satisfactory efficiency.

## Cavitation

All theoretical considerations of the action of water, not only in a turbine but also in any part of the hydro development, are based on the assumption that water is not compressible and consequently does not change its specific weight under different pressure conditions. So far as increase of pressure above atmospheric is concerned, the compressibility of the water is so small that the assumption of incompressibility holds for all practical purposes. With the decrease of pressure below the atmospheric this assumption holds until the pressure is decreased to the evaporation pressure corresponding to the temperature of the water. If the pressure is lowered below that point, then a sudden change in conditions occurs; "cold boiling" of the water takes place and the resulting mixture of water and steam becomes highly compressible. Under these conditions all of the assumptions on which the theoretical design is based become suddenly invalid. A very interesting confirmation of this theory was obtained in some laboratories in Europe, by running comparative turbine model tests on cold and heated water.

The cavitation phenomena are treated in more detail in the paper by L. M. Davis and G. W. Spaulding.* Here it is sufficient to state that the pressure drop depends on the water velocity and acceleration.

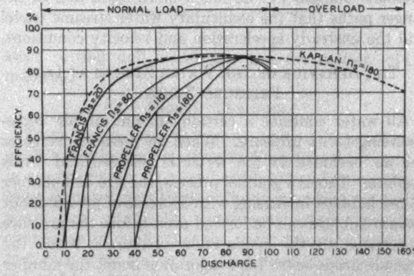

Fig. 7—Comparative Efficiency Curves of Francis, Propeller, and Kaplan Turbines

The pressure and velocity conditions in a water stream passing an immersed body are illustrated by Fig. 8. The velocity reduces practically to zero at the point, *a*, of the immersed body where the maximum pressure occurs. The pressure and velocity changes are clearly shown on the diagram.

Fig. 9 shows the pressure conditions in a water column passing through a pipe with smoothly decreasing and increasing cross-sections. The velocity is highest at the smallest section, where the pressure is lowest, due to the pressure drop caused by accelerated velocity. After passing the smallest section, the water column is retarded, the velocity decreases and the pressure increases as indicated in the diagram by solid lines. If the friction losses are taken into account, the pressure curve will change as indicated by dotted lines.

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*See page 220.

These simple cases show that even in the non-turbulent uniform or non-uniform flow, depending on the velocity and acceleration conditions, any pressure less than the original may be created, even down to the evaporation pressure or lower. Also, depending on the acceleration and retardation of the velocity of the water stream, the pressure may drop below the evaporation pressure at some point in the stream and increase again above that pressure in some succeeding section.

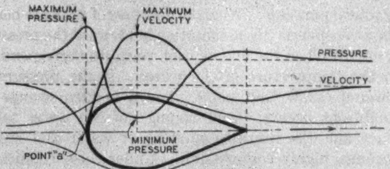

Fig. 8—Velocity and Pressure Diagrams of a Water Stream Passing an Immersed Body

If the water flow is turbulent, then the elementary water streams are to be traced in the eddies, and the pressure changes will be much more rapid due to the longer paths that the elementary water streams travel and the unsteady acceleration and velocity conditions.

## The Behavior of the Water Stream at Low Pressure Zones

All water contains a certain amount of air corresponding to its pressure. When the pressure decreases the air occluded in the water is released and forms bubbles. This is a gradual process, the size and number of the bubbles increasing with decrease of pressure, but certain bubbles can be formed even before the pressure is reduced to the evaporation pressure. When the pressure drops below the evaporation point, the number and size of the bubbles increases very rapidly; these bubbles contain a mixture of air and vapor. So long as the flow is non-turbulent, the lowest pressure—and consequently the formation of bubbles—takes place somewhere along the boundaries of the stream but not inside the water column. In case of turbulent flow the lowest pressure and the formation of bubbles will occur along the center line of the eddy. A certain time element is necessary for the formation of bubbles, and particularly air bubbles, at pressures higher than the evaporation pressure. Water passing very rapidly through a low pressure zone may not release bubbles while water, under the same pressure conditions, but passing more slowly through the low pressure zone, may release a considerable amount of bubbles.

The velocity and acceleration of that part of the water stream which adjoins the boundaries depend to a large extent on the surface conditions of these boundaries; a rough surface may augment the formation of bubbles.

## The Phenomena Accompanying Cavitation

The formation of air bubbles, or air-vapor bubbles, of appreciable size, interrupts the continuity of the water column, or water streams, radically changes their condition, introducing irregularities which preclude theoretical analysis. Nearly all hydraulic machinery functions in accordance with its design provided the continuity and regularity of the water flow are preserved, but if they are destroyed, then the most noticeable result will be the rapid increase in the amount of energy dissipated in the flow coupled with a rapid decrease in efficiency. That, *per se*, would be a perfectly valid reason to avoid cavitation in turbines. But in addition to a decrease in efficiency, cavitation may also result in the destruction by pitting of the affected parts of the turbine. In spite of much research, the way in which pitting actually occurs is not too clear. It seems to be proven that the cavitation bubbles do not have any destructive effect at the place of formation and that destruction by pitting occurs at places where, due to changed velocity conditions, the pressure again rises above the evaporation point with a consequent disappearance of cavitation bubbles.

A number of attempts was made to determine, by mathematical methods, the conditions under which cavitation bubbles disappear. Such determination cannot be considered very exact because it must be based on a number of rather arbitrary assumptions. Those methods, however, confirm the general theory that if a cavitation bubble is contained in a water column or water stream which is under increasing pressure conditions, a rapid squeezing of such bubble occurs. This squeezing results in a rapid increase in temperature within the bubble and when this occurs in contact with a hard substance, it will be accompanied by a localized increase in unit pressure, the intensity of which increases very rapidly with a decrease in the size of the bubble.

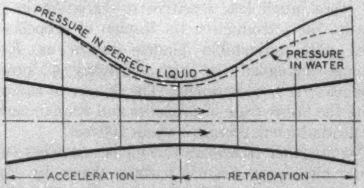

Fig. 9—Pressure Diagrams of an Accelerated and Retarded Water Column

The mechanics of the pitting can be considered as follows:

Bubbles in contact with the surface of some part of the turbine are rapidly diminishing in size and finally collapse with the result that the adjacent metal is bombarded by the residual, very minute particles of air, under tremendous pressure and at high temperatures. At the same time it is probable that such temperature enables the oxygen in the bubble to form a direct chemical reaction with the affected part and this will increase the pitting still further.

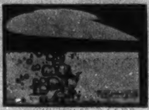

Fig. 10—Glass Model of a Runner Blade Subjected to Cavitation

Cavitation tests which showed that chemically inert glass is much more rapidly destroyed by pitting than any of the commonly used metals seem to support the theory that mechanical action is the most potent factor in pitting. On the other hand, the better cavitation resistance of stainless steel as compared to cast iron or cast steel indicates that the chemical action may be of some importance.

Pitting does not occur in low pressure zones, where the cavitation originates, but rather in rising pressure zones, where the cavitation bubbles are destroyed; this is why the pitted zones are so irregular.

Fig. 10 is an illustration of a glass model of a runner blade which was subjected to cavitation. It shows the formation of cavitation bubbles in the low pressure zone and their disappearance in a zone where the pressure was higher than the evaporation pressure. The bubbles disappeared on that part of the blade where the pitting began. This is the simple case where cavitation bubbles are formed at the surface of the blade in non-turbulent flow and carried by the water flow along the face of the blade into higher pressure zones where the bubbles collapse and in so doing destroy the material of the blade by pitting.

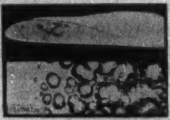

Fig. 11—Glass Model of a Runner Blade with Extended Cavitation Area

The same model blade is shown again in Fig. 11 but under different conditions, which were arranged so that the low pressure area extended along the blade; in this case the bubbles were carried away by the water flow and no pitting occurred on the blade itself. The same thing may occur when cavitation bubbles are formed in a turbulent flow along the center line of an eddy. Such bubbles may be carried irregularly a considerable distance. If they finally reach a high pressure zone without contacting any part of the turbine, they will disappear and merely cause unsteady flow conditions, coupled with the characteristic noise that accompanies cavitation. However, if, in approaching a higher pressure zone, cavitation bubbles come into direct contact with any part of the turbine, they will bombard and pit that particular part.

Fig. 12 shows a cross-section through a cast iron part subjected to cavitation. The spongy appearance was caused by gradual destruction, starting with the particles that offered least resistance. In the case of cast iron, the large graphite particles are easily disintegrated and washed away first and the iron particles are removed afterwards. This picture shows clearly how non-uniformity in the material or rough spots may help to start pitting and accelerate the destruction of the material.

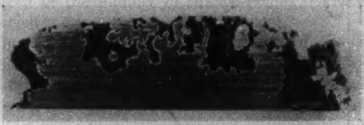

Fig. 12—Cross-Section Through a Cast Iron Part Subjected to Cavitation

## Design Theories

From the instant the water enters the stationary guide vanes in the conservative Francis turbine until it leaves the runner, it is confined between two relatively close adjacent partitions. The parts which guide the water are practically continuous; their curvature changes so gradually that the water does not break contact with them and at the same time it passes through the turbine at moderate velocities so that the friction losses are low and no harmful eddies occur. The customary design method is to assume a very large number of vanes; hence the entering water is divided into an equal number of filaments, in each of which the conditions with respect to every cross-section are constant, and it is sufficient to analyze only the velocities and pressures along the center line of each filament. Under such conditions satisfactory results may be obtained by applying the most simplified one dimensional hydraulic theory, under assumption of a stream line, non-turbulent flow and a perfect liquid the viscosity of which is zero.

In changing to higher specific speed Francis turbines, with rapidly increasing friction and eddy losses, the same design method does not give very satisfactory results and must be checked by model tests to ascertain in each case how close the design satisfies the actual conditions.

In propeller and Kaplan turbines, the water is not guided as it is in the Francis type and none of the assumptions on which the designs of Francis turbines were based are valid. The problem now becomes two or three dimensional, with the velocity and pressure conditions of the water changing not only in the direction of the main flow but at every section taken at right angles to that flow. The hydraulic theories fail entirely and the design becomes a problem in hydrodynamics.

At present complete solution of the general hydrodynamic equations of a physical liquid, the viscosity of which is not zero, is not known. If an attempt is made to handle the hydrodynamic problem, by incorporating the simplifying assumption of a perfect fluid, the viscosity of which is zero, then the theoretical results are so opposed to actual conditions that they cannot be used. Probably the most striking deficiency of the theory is that in such liquid neither can eddies be formed nor can the laminated steady flow be changed to turbulent flow. That makes it necessary to approach the subject in a less formal way by introducing approximate theories which, within certain limitations, give results that for practical purposes are near enough to the actual conditions.

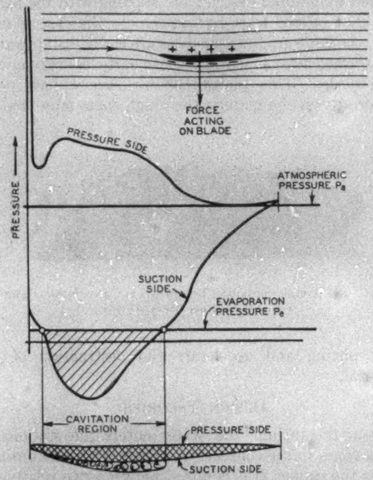

Fig. 13—Pressure Conditions Along the Surfaces of a Single Propeller Runner Blade

Probably the most important of such theories is the boundary layer theory of Prandtl, which is based on the idea that the water column behaves as though water were a perfect liquid. This is due to the very low viscosity of water and no appreciable error is involved if the viscosity is neglected entirely. The important difference occurs only along the boundaries, where the film of water which covers them has the same velocity as the boundaries. Here the difference in the velocities of the adjoining water films may be so large that even the very low viscosity of water will have a considerable influence and cannot be neglected. A rapidly moving water column among immovable boundaries may be considered as such an instance. Consequently, the theory of Prandtl assumes that in its flow the water behaves as a perfect liquid except for a comparatively thin layer that adjoins all boundaries. In this layer the velocity of the water changes from the velocity at the boundaries to the velocity of the main stream.

This theory also gives a satisfactory explanation of the formation of eddies. In the case of retarded velocities the pressure in the boundary layer may become lower than the pressure in the adjoining water stream; then the boundary layer is curled into the higher pressure zones of the main stream, turning in the upstream direction, breaking away from the boundaries and starting an eddy. Such phenomena do not occur under accelerated velocity conditions of the water stream. The results of this theory agree very closely with the actual conditions.

The next in importance is the Kutta-Joukovsky theory concerning the forces acting on a body immersed in the flowing stream of a liquid and the application of this theory to the design of propeller blades. This theory is very simple as long as a single infinitely long blade is considered, but gets complicated when the actual condition of a number of short blades is considered.

All these theories give a possibility to handle the problems mathematically or graphically and are very satisfactory is applied to a steady, laminated flow. They fail entirely if an attempt is made to apply them to a turbulent flow.

## Design of Propeller and Kaplan Turbines

The action of the water column that passes through a propeller or Kaplan turbine can be subdivided into four major parts:

1. The action of the water entering the unit, including the intake, scroll case, guide and regulating vanes or wicket gates, where the water column is divided in a number of streams.

2. The action of the water after it passes the guide vanes and before it strikes the runner blades. Here, due to the way in which the water is guided by the guide and regulating vanes, the water streams are united in a revolving water column that has two distinct velocity components, one parallel to the axis of the turbine and the other rotating around this axis.

3. The action of the water when it strikes the runner blades and the revolving water column is again divided in a number of streams.

4. The action of the water after it leaves the runner and the water streams are united in a column that flows through the draft tube until it reaches the tailrace.

*Water Entering the Unit.* The first part is very much the same in a propeller or Kaplan turbine as in a Francis turbine and may be handled in the same way.

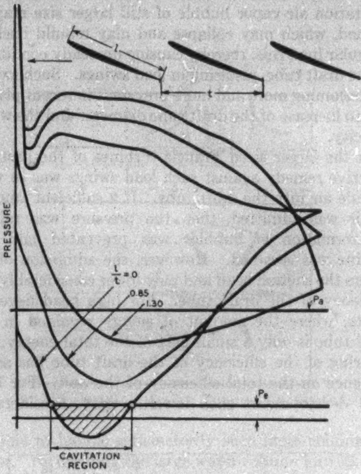

FIG. 14—PRESSURE CONDITIONS ALONG THE SURFACES OF A NUMBER OF PROPELLER RUNNER BLADES

*Revolving Water Column.* The second part, the revolving water column, has no analogy with any part of a conservative Francis turbine. The design problem is to arrange all conditions so that the water comes down with minimum friction and eddy losses, and the rotating water column is long enough so that at its end when the water strikes the runner blades, all nonuniformities are smoothed out and there is no difference between the water streams that strike the different blades.

*Water Passing the Runner.* The third part, the water streams passing between the runner blades, again has no analogy in a Francis turbine. The ideal condition will be obtained if the turbine could be so designed that if the runner were removed the flow of the water column in the direction parallel to its axis would be the same as with the runner in place and would not be disturbed by again installing the runner. In that case the conversion of energy from the revolving water column to the runner blades would be accomplished without any disturbance simply by stopping the rotation of the column, so that after passing the runner the water column would enter the draft tube and flow through it with only a velocity component parallel to its axis and with no circumferential velocity components. Such conditions can hardly be obtained in the practical design and in most cases only a partial retardation of the rotation of the water column can be accomplished.

Fig. 13 shows the pressure conditions of a water stream passing a single blade. Fig. 14 shows to what extent in similar runner designs a change of the number of blades will influence the pressure conditions. The upper part of this diagram shows a developed circumferential section taken parallel to the axis of the runner. Since $l$ is the width of the blade and $t$ the spacing, the ratio $\frac{l}{t} = 0$ denotes the conditions of a single runner blade. The other values of $\frac{l}{t}$ show different numbers of blades. The pressure, $P_a$, is the atmospheric pressure. The pressure, $P_e$, is the evaporation pressure of the water. The shaded area below $P_e$ shows the cavitation region at the suction side of the blade.

This diagram shows that the value of $t$ has to be reduced or the number of runner blades increased to diminish or remove the cavitation danger.

Fig. 15 shows the average pressure of the water passing through the turbine; the lowest average pressure occurs at the draft tube inlet. But in the individual water streams that pass between the runner blades the pressure may be considerably lower than shown in this diagram.

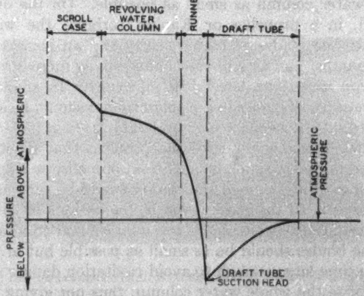

FIG. 15—AVERAGE PRESSURE CONDITIONS OF A WATER COLUMN PASSING THROUGH A TURBINE

The superimposing of the diagrams of Figs. 14 and 15 will show that the part of the water stream which passes along the pressure side of the blade will have a pressure higher than the pressure at the draft tube inlet. On the contrary, that part of the water stream which passes the suction side of the blade will show lower pressure than the pressure at the draft tube inlet. These pressure differences are essential in the turbine, since they are converted into forces that rotate the runner, converting the energy of the water into mechanical energy that is transmitted through the shaft to the generator.

In order to increase the forces acting on the blades, it is necessary to increase the pressure difference between the two sides of the blade, which in turn will retard more effectively the rotation of the water column.

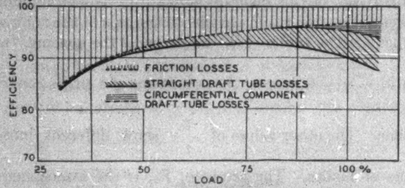

Fig. 16—Losses of a Kaplan Turbine

The amount of pressure drop on the suction side of the blades depends upon the shape and number of the blades, and the force that is to be transmitted from the water streams into each individual blade. In order to reduce the cavitation danger the force per unit of blade surface that is transmitted from the water streams into the runner should be as small as possible. This means that the total area of the runner blades should be as large as possible and the retardation of the rotation of the water column as small as possible. On the other hand, in a propeller or Kaplan turbine, the water strikes the blades at high velocity and an increase in the number and area of the blades rapidly increases the friction losses and lowers the efficiency. In addition, the number of blades in a Kaplan runner should be kept low to satisfy mechanical considerations.

The foregoing indicates the problem that must be solved in designing a highly efficient propeller or Kaplan turbine. The shape of the blades should be such as to correspond to the most favorable conditions in so far as cavitation is concerned; the number and total area of the blades should be as small as possible but at the same time large enough to avoid cavitation danger and to utilize the whole water column, thus not giving the water a chance to escape between the blades without performing useful work.

*Water Passing the Draft Tube.* The fourth part—the action of the water in the draft tube—is very similar to the Francis turbine. The principal difference is that the higher velocity under which the water enters the tube makes it necessary to regain a much higher percentage of energy in the draft tube. This means that the draft tube efficiency has a larger influence on the total efficiency of the unit. At the same time the size of the draft tube and the large amount of water make such turbines very sensitive to irregular conditions and disturbances in the draft tube. Probably the most sensitive section is where the water leaves the runner and enters the draft tube. Here the water does not represent a uniform, solid column, but close to the axis of the turbine there is formed a low pressure area which is filled mostly with air and which extends into the tube. If, due to deficiencies of design, the air is not carried away by the water, an air bubble of considerable size may be formed. If the pressure at this point is lower than the evaporation pressure of the water, then a cavitation air-vapor bubble of still larger size may be formed, which may collapse and may rebuild itself at irregular intervals, thereby causing unsteady conditions in the draft tube, resulting in load swings. Such swings are becoming more and more prevalent in recent plants, due to increase of the draft tube diameter and the water velocity.

In the larger sized Francis turbines of the past, an effective remedy against such load swings was to vent outside air into the draft tube. If a sufficient amount of air was admitted, then the pressure was raised, the formation of bubbles was prevented and the turbine was steadied. However, the admission of air lowers the suction head and may lower considerably the efficiency of the draft tube. For high head developments, where the amount of energy regained in the draft tube is only a small part of the total energy, the lowering of the efficiency of the draft tube has small influence on the total efficiency of the unit. For low-head developments such lowering may considerably influence the total efficiency of the unit. Here, as in many other cases, a turbine of high efficiency is much more sensitive to outside disturbances than a low efficiency turbine. High efficiency requires not only a unit better designed but also better protected against all disturbing influences. Since it is not reasonable to build and pay for a high efficiency turbine and afterward lower its efficiency by admitting air in order to have it run steady, considerable effort was spent in

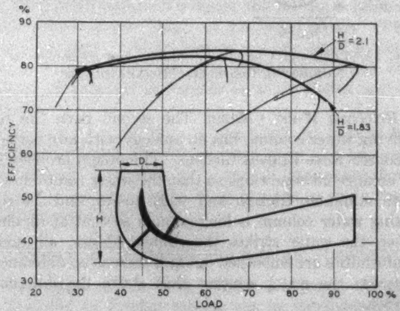

Fig. 17—Comparative Efficiency Curves of Draft Tubes of Different Height

investigating the conditions and finding ways to build highly efficient, steady units. The first step was made by Professor Kaplan, who increased considerably the size of the end piece of the runner forming the familiar heavy hub of the propeller and Kaplan turbines; this decreased considerably, and at the most vulnerable point, the size of the bubble that could form.

The next step, taken in Europe, was based on the idea that with a constant increase of the size of the draft tube the conditions are rapidly approached that make it impossible to handle satisfactorily such large columns of water. By dividing the large water column into smaller ones, much more satisfactory conditions were obtained. In the beginning this idea was prompted by structural considerations where in the larger units the size of the outlet of the tube increased to such extent that structural difficulties were encountered. The result was the introduction of vertical partitions in the draft tube outlets. These partitions were very helpful structurally and being built in the horizontal part of the tube, far from the runner, they exerted only a slight influence on the hydraulic conditions. Next, baffles were tried at right angles to the vertical partitions, but starting close to the runner. The first tests of such baffles showed that although they considerably steadied the unit, they lowered the efficiency.

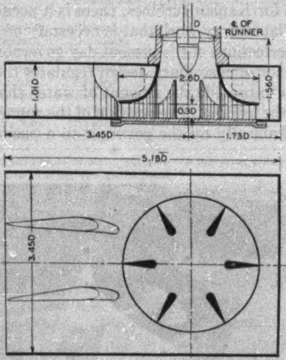

Fig. 18—Shallow Draft Tube of Spannhake

Further investigation disclosed that the reduction in efficiency is due principally to the circumferential component of the velocity of the water column as it leaves the runner. If this component was considerable, then the baffle broke it up and prevented the regaining of the energy in that component or, in other words, the baffles were very beneficial for axial flow and detrimental for rotating flow.

It was found that a satisfactory compromise can be made by moving the baffles away from the runner to a point where their unfavorable influence on the efficiency was small but still in a region where the division of the water column was effective in steadying the draft tube conditions and the loading characteristics of the unit. Such baffles are used in most of the larger sized units designed in Germany and Switzerland.

Fig. 16 gives an idea of the distribution of losses in a Kaplan turbine. First and most important are the runner friction losses, which are mainly responsible for the low efficiency at smaller loadings. Second, the straight draft tube losses, which are very small at partial loadings but increase with the increase of load. Third, the draft tube losses due to the circumferential velocity component which in this particular turbine appear only at high loadings.

The major part of the losses at high loadings are draft tube losses and great effort was made to diminish them. Fig. 17 shows the results of investigations on Kaplan turbines with elbow type draft tubes, and shows the favorable influence of the increased height of the tube, but this is very expensive, since it necessitates deep excavation and extra concrete. Therefore, research was made to find the most favorable type of shallow draft tube.

The very shallow design shown by Fig. 18 was developed after considerable research work on draft tube models by Professor Spannhake in Karlsruhe. The idea of dividing the water column after it leaves the runner is treated in an original and interesting way. By means of partitions the vertical part of the water column is divided into six and the horizontal part into three streams. At the same time the central part of the vertical water column is not interfered with. This design suggests that further improvement is possible in developing designs which will enable the energy to regain to a larger extent the circumferential component of the water velocity.

Fig. 19—Stainless Steel Runner of the Swir Unit (No. 10)

## Research

Recent low-head developments in the United States show conclusively the insufficient amount of theoretical and model research work that has been done in connection with the development of hydraulic machinery.

The contention, so common in the past, that laboratory research can be substituted by observation or study of units in actual operation is very misleading. The operation of the finished unit is the supreme test of all theoretical and laboratory work on which the design was based. But the many factors involved, which cannot be separated in the operating plant, presents a problem so complicated that probably only in exceptional cases can valid conclusions be reached by a study of operating conditions. The proper study necessitates the separation of the different problems and their independent solution. In most cases this can be done economically only in the laboratory.

Instead of limiting the laboratory work to the customary efficiency determinations, a number of new and important laboratory investigations is necessary. The most spectacular are the cavitation problems. The theoretical considerations concerning cavitation can be determined only in the laboratory.

The first fundamental question is, under what operation conditions will cavitation begin in a certain unit? Next, what can be done so far as the design of the runner and all other parts of the turbine are concerned to eliminate cavitation and to permit either a higher specified speed or a higher setting? Finally, can the turbine be run under the conditions at which cavitation will start but be so slight as to be tolerated?

So far as efficiency is concerned, a reasonably smooth cast runner without machining or surfacing will probably show the same efficiency as a similar runner machined and highly polished. So far as cavitation is concerned, a remarkable and surprising difference may be obtained by the substitution in the prototype of machined and polished surfaces for the rough surfaces of castings. The European practise follows the only logical way, which is first to determine by model experiments in the laboratory the best shape of the runner blades and then to build an exact prototype, machined and polished on all surfaces which come in contact with flowing water.

One of the important researches in connection with cavitation is that pursued in Sweden and Germany in establishing the relative corrosion resistance of different materials. Obviously, it is necessary to know which of the available materials best resists corrosion. Sample plates of different materials were kept in flowing water under conditions of cavitation. The series of materials so far investigated begins with glass, which was found to have the least resistance, and ends with stainless chromium steel which has the greatest resistance.

A considerable amount of theoretical data necessary to design runner blades is based on the laboratory work made in aero-dynamic laboratories in connection with airplane propellers. Theoretically and practically, there is a similarity between the conditions of a uniform flow of water impinging against the blades of a propeller or Kaplan turbine, and a uniform flow of air against the blades of an air propeller. Since tests on air models are much simpler and much more feasible than on water models, it is clear why so many important contributions to the theoretical design of propeller and Kaplan turbines came from aero-dynamic laboratories. Many of the present investigations in hydraulic laboratories consist of picking up threads left by the aero-dynamic investigations.

Finally, for Kaplan turbines, there is a peculiar field of tedious laboratory work that is necessary on account of the imperfections of the present day governor design. The governor of customary design regulates the wicket gates so as to provide the amount of water that corresponds to the loading. The position of the runner blades is set mechanically by the governor to a position that was predetermined by laboratory tests. In so far as the efficiency is concerned, the relationship which gives the most favorable combination between the opening of the wicket gates and position of the runner blades changes with varying head and a considerable number of laboratory tests are necessary to cover all operating conditions. Even after that is done, it may be necessary to check this information by actual operation tests.

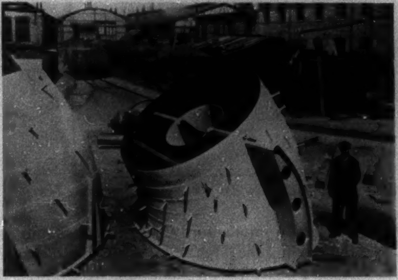

FIG. 20—STEEL LINER OF DRAFT TUBE INLET OF THE WETTINGEN UNIT (No. 2)

Notice the baffle liner and the stationary extension of the runner hub

## LARGE SIZED KAPLAN TURBINES

The data available pertaining to the more important recent developments are collected in Table I. At present there are two different designs of the larger sized Kaplan turbines, the German-Swiss design, which is followed very closely by the latest American designs, and the Swedish designs. The main difference is in the location of the servo-motor for operating the runner blades. In the German-Swiss designs, the servo-motor

TABLE I—LARGE SIZED KAPLAN TURBINES

| Number | Development | Country | Manufacturer | Head in ft. | Output in hp. | Revolutions per minute | Discharge in c.f.s. | Diameter of runner in ft. | Specific speed | No. of runner blades | Draft tube baffle | Material of runner blades | Surface of runner blades |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (1) | | | | | | | | (2) | (3) | (4) |
| 1 | Shannon | Ireland | V | 106.5 | 33,000 | | | 13.15 | | 7 | | St | m |
| 2 | Wettingen | Switzerland | E | 76.3 | 10,700 | 214.0 | 1,425 | | 98 | 6 | B | | m |
| 3 | Gronvollfoss | Norway | V | 75.5 | 18,400 | | 2,650 | | | 6 | | C | m |
| 4 | Sages | Russia | K | 65.7 | 17,000 | 167.0 | | | 119 | | | St | |
| 5 | Mixnitz | Austria | V | 64.4 | 12,150 | 215.0 | 1,940 | 10.05 | 143 | 6 | | C | m |
| 6 | Safe Harbor | U. S. A | S, M | 55.0 | 42,500 | 109.1 | 8,000 | 18.33 | 151 | 5 | no | C | |
| 7 | Munkfors | Sweden | K | 50.5 | 15,000 | 167.0 | | 12.15 | 151 | | | St | |
| 8 | Eching | Germany | E | 39.4 | 12,000 | 167.0 | 3 155 | 13.12 | 168 | | B | C | m |
| 9 | Ryburg | Germany-Switzerland | V, E, C | 37.7 | 38,700 | 75.0 | 10,420 | 22.97 | 157 | 5 | B | C | m |
| 10 | Swir | Russia | K | 36.1 | 37,500 | 75.0 | 10,240 | 24.35 | 164 | 5 | | St | |
| 11 | Abborfors | Finland | K | 35.8 | 16,000 | 107.0 | 4,520 | 14.96 | 155 | | | St | |
| 12 | Dogern | Germany-Switzerland | E | 35.1 | 35,500 | 75.0 | 10,600 | 22.97 | 166 | 5 | B | C | m |
| 13 | Lauforsen | Sweden | K | 30.3 | 13,000 | 94.0 | 4,310 | 15.65 | 151 | | | St | |
| 14 | Laholm | Sweden | K | 27.9 | 16,000 | 83.3 | 5,860 | 18.05 | 164 | | | St | |
| 15 | Klingnay | Switzerland | V | 26.9 | 20,000 | | 7,070 | | | | | C | m |
| 16 | Klingnay | Switzerland | E | 23.5 | 18,400 | | 8,160 | 21.20 | | | | C | m |
| 17 | Lilla Edet | Sweden | K | 21.3 | 11,200 | 62.50 | 5,155 | 19.03 | 144 | 4 | no | | |
| 18 | Vargon | Sweden | K | 14.1 | 15,200 | 46.90 | 11,090 | 26.25 | 211 | 4 | no | St | |

(1) For the names of manufacturers the following abbreviations are used:
C—Ateliers des Charmilles—Switzerland.
E—Escher-Wyss—Switzerland.
K—Verkstaden Kristinehamn—Sweden.
M—I. P. Morris Division—Baldwin-Southwork Corporation—United States.
S—S. Morgan Smith Company—United States.
V—J. M. Voith—Germany.

(2) B—indicates a baffle in the draft tube.
no—indicates no baffle in the draft tube.
(3) St—indicates stainless steel.
C—indicates cast steel.
(4) m—indicates that the surfaces of the runner blades are machined.

is located above the runner between the turbine and generator shafts, and the shaft that moves vertically to operate the blades is located in the hollow turbine shaft. The servo-motor is operated by pressure oil which is admitted through the hollow generator shaft. The Ryburg and Safe Harbor units are typical examples.

In the Swedish design of Kaplan runners the servo-motor for operating the runner blades is placed within the runner and the operating pressure oil is admitted through the hollow generator and turbine shaft. Fig. 19 shows such a runner of the Swir development, listed in the table under 10. Note in the table the extended use of stainless steel for the Swedish designed Kaplan runners.

The very scant information available concerning the height at which the center line of the units is set with reference to the normal tail water elevation is given for the developments 5, 6, 9, 17 and 18 in the following table:

TABLE II

| Number | Development | Head in ft. | Center line of runner blades above (+) or below (−) the normal tail water elevation in feet |
|---|---|---|---|
| 5 | Mixnitz | 64.4 | − 1.64 |
| 6 | Safe Harbor | 55.0 | − 6.91 |
| 9 | Ryburg | 37.7 | + 1.30 |
| 17 | Lilla Edet | 21.3 | + 3.20 |
| 18 | Vargon | 14.1 | +14.00 |

## KAPLAN AND PROPELLER TURBINES FOR HIGHER HEADS

There is a considerable tendency to increase the maximum head for which Kaplan and propeller turbines may be used, but two principal handicaps must be overcome:

1. The cavitation danger. In so far as the average runner conditions are concerned, the lowest pressure at the draft tube entrance, shown by Fig. 15, can be kept well above the evaporation pressure. The difficulty lies in avoiding local low pressure areas on the runner blades. Apparently by increasing the diameter of the center piece, or hub, of the runner and reshaping the deflector, or end piece, the conditions can be improved and Kaplan or propeller turbines for still higher heads are feasible. An attempt in this direction is illustrated in Fig. 20, which shows the stationary extension of the runner hub in the draft tube baffle. This design is used in connection with the 10,000 hp., 76 ft. head, Kaplan units of the Wettingen development in Switzerland and is listed in the table under 2.

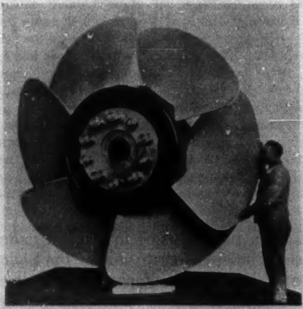

FIG. 21—RUNNER OF THE WETTINGEN UNIT (No. 2)

2. The rapidly increasing cost of Kaplan turbines for higher heads. This is due to the greater forces acting on the runner blades and as a consequence the necessary increase of the size of the runner hub as compared with the diameter of the runner.

Fig. 21 shows the runner of the same Wettingen development and gives an idea of the size of the hub as compared with the overall size of the runner.

In Table III is given the information pertaining to the comparative size of the hub and runner for the developments 5, 6 and 9:

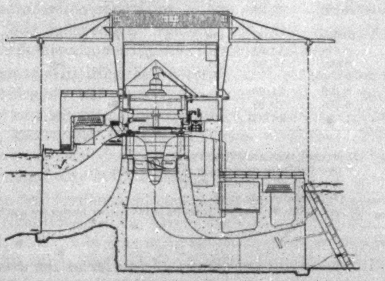

Fig. 22—Cross-Section of the Vargon Unit with Syphon Arrangement (No. 18)

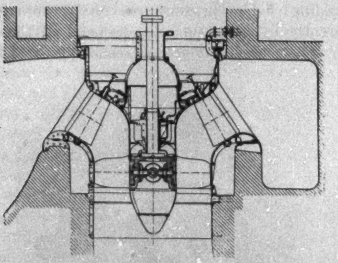

Fig. 23—Cross-Section of a Runner with Inclined Wicket Gates

The Kaplan turbine listed in Table I under 1, the just recently ordered fourth unit of the Shannon development in Ireland, is of particular interest. Not only is the present head of 82.25 feet the highest for which a Kaplan turbine was ever designed, but this turbine is expected to perform satisfactorily even under the future head of 106.5 feet.

TABLE III

| Number | Development | Head in ft. | Diameter of runner in ft. | Diameter of hub in ft. | Ratio of diameters hub/runner |
|---|---|---|---|---|---|
| 5 | Mixnitz | 64.4 | 10.05 | 4.24 | 0.423 |
| 6 | Safe Harbor | 55.0 | 18.33 | 7.20 | 0.393 |
| 9 | Ryburg | 37.7 | 22.97 | 9.85 | 0.428 |

The very radical change that would be involved in materially increasing the head by putting two propeller or Kaplan runners in series has not yet been tried out in practise.

## KAPLAN AND PROPELLER TURBINES FOR VERY LOW HEADS

For very low heads the problem is to reduce the cost of handling large amounts of water. The ordinary Kaplan or propeller turbine arrangement requires large amounts of excavation and concrete. The latest trend is to reduce this expense by more suitable arrangements.

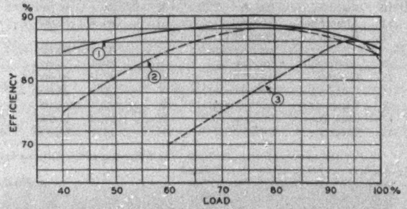

Fig. 24—Comparative Efficiency Curves of a Conventional Kaplan, a Kaplan with Fixed Gates, and a Propeller Turbine

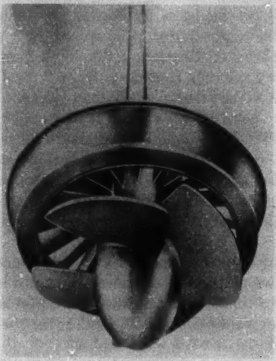

Fig. 25—Kaplan Runner of a Turbine Without Wicket Gates

Fig. 22 shows the largest turbine built, in so far as physical dimensions are concerned. This turbine is located so high that the water entering the turbine must be raised higher than the forebay level. To start the turbine a pump is provided to create a partial vacuum in the space above the runner. After the water starts to flow through the runner, the pump is stopped and the unit operates as an ordinary turbine. To shut down the unit, it is only necessary to admit air which breaks the syphon and stops the water flow. The power house is of the out-door type; the generators are protected by metal covers serviced by a 200-ton gantry crane. This arrangement was adopted in the Vargon development on the Gota River in Sweden and is listed in the table under 18. The simplicity and low cost of this plant and the absence of the expensive head gates opens quite a number of possibilities for similar developments.

An economical arrangement may be obtained by reducing the overall dimensions of the turbine; this can be accomplished by inclining the wicket gates, as illustrated by Fig. 23. This arrangement necessitates a complicated and expensive gate regulating mechanism. A much simpler and less expensive design can be secured by omitting the gates, thus leaving only the guide vanes and regulating the turbine by means of the runner blades only. Fig. 24 shows the efficiency sacrifice by such an arrangement. Curve 1 is for a Kaplan turbine regulated in the customary way, the governor acting on the wicket gates, and the runner blades are set to correspond with the opening of the wicket gates. Curve 3 is for the same turbine when operated as a propeller turbine with fixed blades. Curve 2 is for a Kaplan turbine with locked wicket gates, with the governor controlling only the runner blades. This flat curve shows much more favorable efficiency than a propeller turbine with only a small sacrifice in maximum efficiency which makes the operation of such a unit very satisfactory.

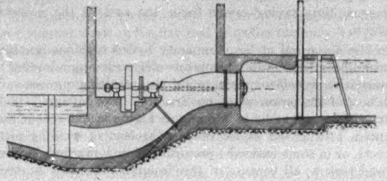

FIG. 26—CROSS-SECTION OF A KAPLAN TURBINE UNIT FOR VERY LOW HEADS

These curves indicate that the customary regulator of a Kaplan turbine, *i. e.*, the governor acting on the wicket gates, may be improved by reversing the conditions and making the governor act on the runner blades and setting the wicket gates mechanically to correspond with the position of the runner blades.

A Kaplan runner with fixed wicket gates is shown by Fig. 25. A very economical design for such a turbine operating under a very low head is shown by Fig. 26. The horizontal shaft of the unit and its low overall dimensions make it possible to build a power house which requires a minimum amount of excavation and concrete.

The combination of fixed inclined guide vanes with a vertical syphon or horizontal unit probably represents the most economical design possible for developments operating under very low heads. A number of such units located along a river and with automatic or remote control, opens development possibilities which were considered economically impossible only a few years ago.

### ACKNOWLEDGMENTS

The presentation of this paper was made possible by the support received by the author from Messrs. E. S. Fickes and James W. Rickey, respectively Vice President and Chief Hydraulic Engineer of the Aluminum Company of America, and J. R. Baker, Chairman of the Institute Committee on Power Generation.

## Discussion

**Harry E. Popp:** Unquestionably the economical development of our low-head powers is becoming increasingly important, and the Kaplan adjustable blade turbine, as developed in Europe, furnishes a valuable means of promoting that development. The writer, however, cannot agree with Mr. Karpov that credit for past accomplishment is due entirely to European engineers.

The so-called Kaplan turbine is in reality the combination of the adjustable blade runner and its control mechanism with the usual form of scroll case, draft tube, and miscellaneous mechanical details independently developed and perfected by American engineers. American hydraulic turbine manufacturers by painstaking effort have kept pace with the requirements of the hydroelectric industry in this country as many of their record-making achievements testify. European and American designers have always pursued distinctly different courses. The former have developed elaborate mathematical theories of hydrodynamics as the basis for their designs; the latter have been content with the simpler theories supplemented, however, by painstaking experimental work. This work began with the improvement of runner design at the Holyoke testing flume; it was extended by the several turbine manufacturers to more elaborate testing of runners and other details in their own laboratories; it grew to include the testing and development of competitive types of draft tubes and scroll cases and more recently the experimental investigation of complete models of proposed hydro stations. American manufacturers have spent generously for hydraulic laboratories and for experimental research on their own account and their facilities have been available at nominal expense to power company engineers who have desired to undertake special development work. Not only has the American method resulted in constant improvement in performance and reliability but it has also permitted the maintenance of an economic balance between the cost and value of such improvements.

It is this balance which will determine the extent to which the adjustable blade Kaplan turbine will find application in our future developments. It must not be supposed that it will find universal use in every one of our low-head projects. Nor is there reason to suppose that the adjustable blade runner would not have been adopted at an earlier date in this country had there been a real economic demand for this type of unit. The writer believes that its adoption at this date, several years after its development in Europe, is merely an indication of the different underlying conditions in the hydroelectric industry here and abroad rather than any reflection on the ability or foresightedness of American designers and manufacturers.

In his chapter on draft tubes Mr. Karpov lays considerable stress on the work done in Europe on the development of "shallow" tubes, on the use of baffles and on the regain of the circumferential component of draft tube velocity. All of these have been investigated in America and the results have had wide publicity. N.E.L.A. publication No. 047 of May, 1930, contains the reports of tests of model draft tubes of various shapes and proportions, both of the elbow and concentric types, dating back to 1922. It is interesting to note that, in simplicity and limiting dimensions, the draft tubes developed in these and other tests compare very favorably with the most modern foreign designs. American experience has been that baffles and partitions add but very little to the performance of a properly designed draft tube and that for structural reasons their elimination is desirable.

At the moment, attention is being concentrated on the spectacular subject of "cavitation" and credit is due to European engineers for initiating the investigation of this phenomenon. Certainly, any investigation, theoretical or experimental, which has for its object the elimination of large loss of efficiency or of capacity or of disastrous pitting should be encouraged, but it should not be permitted to overshadow the equally valuable work which has been done and which remains to be done in other directions.

There is also the grave danger that overemphasis of some particular phase of design may lead to the introduction of costly practises which are not justified by the ends obtained. This is especially true of a subject as interesting as cavitation. In this connection the writer is unable to agree with the authors' conclusions that European practise, which is to machine and polish all runner blade surfaces in contact with flowing water, is the only logical way to build runners, especially since, as the author points out, such machining or surfacing has no effect on the efficiency. By its very nature this machining of the blade surfaces is an extremely expensive operation and if its sole purpose is positively to eliminate pitting which might otherwise only be slight and easily repaired by welding, then this practise can not be said to be either logical or justifiable.

The New England Power System contains upwards of 500,000 horsepower of installed capacity in hydraulic turbines with heads ranging from 20 ft to nearly 400 ft, including one installation of fixed blade and adjustable blade propeller wheels. Not one case of real serious pitting has ever occurred on the entire system. Such minor pitting as does develop is periodically repaired by welding. Until there is real economic justification for complete machining of the runner surfaces and for the use of expensive stainless steel, the writer believes it would be most unwise to make these practises universal in this country simply because the tendency is in this direction in Europe.

Our pressing need in the furtherance of our hydroelectric developments, especially those with low heads, in competition with steam power, is the reduction of first cost wherever possible. This can only be done by simplification, by careful attention to details of design and construction and by carefully balancing cost against return on the investment before accepting any new practises, however attractive they may appear from a theoretical standpoint.

**L. F. Harza:** The author's paper is a thorough resumé of existing European low-head practise and problems, especially those of turbines and draft tubes.

The reduction in station cost by high speed units of conventional design is confined largely to saving in generator cost, but to some extent also in structure cost.

The higher cost of Kaplan turbines as compared with fixed blade propellers finds its justification in a very much improved efficient range of operation. There is hope that the newly introduced fixed gate, moveable blade Kaplan turbine will much further reduce station structure as well as turbine costs.

American manufactures have lagged in low head and high speed turbine design and there is great need of cavitation laboratories for solution of problems vital to all high speed turbines. The Safe Harbor Water Power Corp. is to be commended for introducing the first one in the United States.

It should be pointed out that the type of station shown in the author's Fig. 22, Vargon, is limited to a head so low that the turbine can be set above head water without exceeding allowable height above tailwater. It is open to question whether the draft head, 14.1 ft, at Vargon does not already exceed the limit of safe draft head for the very high specific speed of 211.

It is an individual problem, as to whether anything is saved by the horizontal installation of the author's Fig. 26. The draft tube problem is complicated, the building width greater, and high tailwater requires design of the generator room walls for outside pressure, and the building as a whole for buoyancy, with drainage pumps to remove leakage.

The daring displayed by European manufacturers in extending the head range of Kaplan turbines to 106.5 feet is commendable and could only be accomplished by the thorough European research complex, and the cavitation laboratories, numerous in Europe.

**James W. Rickey:** In the writer's opinion, the future development of low and medium head hydroelectric projects in the United States depends on obtaining lower plant cost through greater economy in the design of both plant and equipment. Such improved design can be achieved only when the manufacturer and the user of turbines adopt a radically different attitude toward the scientific side of concurrent turbine design and laboratory tests. Heretofore, a lack of engineering knowledge and an unwillingness to incur the expenditure necessary to acquire such knowledge has resulted in unjustifiably increasing the cost of hydroelectric developments. A reasonable amount of money invested in research would often have eliminated expensive operating troubles and also would have reduced the initial investment, thus saving many times the cost of the necessary research.

In the designing of large capacity hydro turbines ignorance regarding cavitation often has been safeguarded by adopting too conservative specific speeds, with the resulting unnecessarily high cost of the power plant but freedom from pitting. On the contrary, in some plants where too high specific speeds were adopted, pitting was excessive and the cost of welding pitted runners, or in some cases the providing of new runners, has been beyond reason; all because of the designer's inability to design for specific conditions runners free from cavitation. These designers deserve much credit for what they have accomplished but the question arises "have they done enough?" The writer believes that the answer is "no" and that if more time be devoted henceforth to the scientific development of new ideas, they should accomplish far more in the next few years than they have accomplished in the past decade.

The author's present and earlier papers on high specific speed turbines indicate one excellent way of attacking the problem of building less expensive and, at the same time, better hydroelectric plants. Of prime importance in this connection is the fact that in the United States there seems to be a woeful lack of appreciation of the necessity for exhaustive theoretical research checked by proper laboratory tests.

In the hope of improving this situation the writer called, in November 1929, a conference of about 30 representatives of hydraulic turbine manufacturers and users to discuss means of providing suitable cavitation laboratories which are essential for a proper study of turbine pitting, there being then several such laboratories in Europe but not a single one in the United States. All attending this conference unanimously admitted that such laboratories are necessary. Today there are a half dozen or more such laboratories in Europe but only one in the United States and that is owned, not by a turbine manufacturer but by a power company! How can our manufacturers hope to develop big propeller or Kaplan type turbines without suitable cavitation laboratories? Some day, in the not too-distant future, the development of the International Section of the Saint Lawrence River will cause orders for approximately 2,200,000 hp of turbines to be dangled before their eyes. Is it not almost axiomatic that the manufacturer who can best prove his ability to deliver the goods will be the favored one?

Looked at from another standpoint, this failure of the hydro turbine manufacturers to provide proper laboratories is, in the writer's opinion, a very short-sighted policy because the steam turbine, coupled with the very efficient boilers now available, is surely giving our undeveloped hydro projects a real "run for their money." Hydro energy from many such projects throughout the country, if developed under today's standards, would cost more per kwhr than if generated by steam and the limit of efficiency in the steam units has not yet been reached. The remedy is obvious.

If the hydro turbine is to compete successfully with the steam turbine in the development of many of our remaining potential water powers there must be a radical improvement in the high specific speed turbine.

The paper presents a valuable resumé of the latest theories, laboratory research and their practical applications. It emphasizes the urgent necessity for much additional work and should be used as a stepping-stone to increase our knowledge along these lines.

**Frank H. Rogers:** In Mr. Karpov's paper, he has described in a very interesting manner the development of propeller and Kaplan turbines and has shown the various steps accomplished and the problems which had to be solved in the evolution from the original slow speed Francis turbine to the modern high speed propeller unit. He has also presented valuable data on the large size Kaplan units recently installed and under construction in Europe.

Mr. Karpov, in giving credit to European engineers for their development work on Kaplan and propeller turbines, has perhaps unintentionally reflected most unfairly on the contributions of American engineers. His statements that "The credit for this past accomplishment was due entirely to European engineers" and "The conditions in the States were unsatisfactory and the turbine manufacturers were unable to make the model tests so essential to the development and proper design of Kaplan and propeller turbines" do not represent the facts.

When in 1921 the Great Falls Development of the Manitoba Power Co. was undertaken, no propeller turbines of over a few hundred horsepower had been constructed, and none had been installed for heads much over 10 or 20 feet. When the Dominion Engineering Works Limited proposed I. P. Morris propeller turbines of 28,000 hp unit capacity for a head of 56 ft, statements were made that propeller turbines would not work under such a head, and some engineers advised that high speed propeller turbines could not be safely used for heads of over 30 ft. The engineers of the Morris Co. at that time developed a cavitation theory for the propeller turbine, utilizing data from marine propeller experience; and on the basis of these calculations proceeded to design the units, which were installed in 1922 and have been successfully operating ever since, and have been followed by additional units of the same design in this plant; and by many other notable installations subsequently carried out. Mr. Karpov in tabulating recent installations includes only one American plant. The total horsepower of American and Canadian installations of I. P. Morris propeller turbines aggregate 876,886 hp, to mention only one company and its Canadian associate. It may be mentioned that very high efficiencies have been secured in American installations of propeller units, such for example as the Dolby plant of the Great Northern Paper Co. (I. P. Morris) giving 93.5 per cent, and the Cumberland County Power and Light Company's West Buxton Station giving 92.1 per cent.

The theoretical basis on which the propeller turbine was made applicable to a large range of heads, and on which its use could be extended with confidence to units of major size, considered the blade area proportions with reference to the cavitation limits imposed by the relation between effective head, draft head and barometric pressure. It was demonstrated that in order to avoid cavitation and to provide stability of operation, the narrow bladed runners of the original Kaplan type, in which the blade area was in the order of one-half of the transverse area of the runner passage, must be abandoned and blade areas must be provided approaching an order of magnitude equal substantially to the complete area of the circular passage or the so-called disk area of the runner. In the face of the earlier teachings that only by a great reduction in area could successful propeller turbines of high specific speed be produced, it was demonstrated that equal or greater efficiencies could be secured by the use of large areas for the blades and that by this means stability of operation and freedom from cavitation could be secured for a head range more than double that which had previously been attempted. This step first proposed by Mr. Moody (an American engineer) is considered to have been one of the most notable advances in the history of the development of the propeller turbine. The theories just mentioned and the results secured by their use were set forth in the paper by Messrs. H. B. Taylor and L. F. Moody presented at the Hydroelectric Conference in Philadelphia in 1922. The development and crystallization of the theory of cavitation were greatly advanced by Dr. Thoma, of Munich, who clearly showed the dimensional relations involved. In his paper on Water Power Research, presented at the World Power Conference in 1924, Dr. Thoma mentioned that "The same result can be obtained from H. B. Taylor's and L. F. Moody's theoretical deductions which were put before the Hydroelectric Conference in Philadelphia in 1922 and which rest upon special assumptions regarding the flow."

In the portion of Mr. Karpov's paper on the design of propeller turbines he describes the importance of making the total area of the runner blades as large as possible in order to reduce the force per unit of blade surface and thus reduce the cavitation danger. He points out, however, that in this type unit the water strikes the blades at high velocity so that an increase in the area of the blades rapidly increases the friction losses and lowers the efficiency. These points were recognized in 1921 when the Manitoba units were built and the difficulty solved in the following manner:

1. A six-bladed runner was adopted with large blade area to prevent cavitation.
2. The blades were designed to reduce velocities of the water with respect to the vane to keep the friction losses within reason. This design results in a circumferential or whirl component of the water leaving the runner.
3. A Moody spreading draft tube was used to regain this whirl component in an efficient manner.

It may be of interest in clearing up the history of propeller turbine development to quote from an article by Dr. Thoma on "Cavitation in Hydraulic Turbines," published in the *Wasserkraft-Jahrbuch* of 1924. Dr. Thoma recapitulates the history of affairs up to that time as follows (freely translated).

"After Kaplan had advanced the suggestion of building turbines with very small vane surfaces and when after the conclusion of the necessary tests the possibility was opened for the practical use of the Kaplan turbine, the danger of cavitation became much more acute. The Kaplan runners looked about like ship propellers with small blade surfaces. The tests at first had only been made with low heads; Kaplan had worked with a head of about 0.6 m and the tests of the Kaplan turbine syndicate had also been made with a head of about 3 m only. The experience with ship propellers and theoretical considerations led to the prediction that at an increase of head cavitation would soon appear. . . . When more than five years ago I first called attention to the danger of cavitation, I met universal unbelief. The general opinion was that this did not happen to water turbines. Today I am blamed in the opposite direction for having judged the sphere of application concerning the Kaplan turbine too small (heads below 5 to 10 m). This criticism is justified, in so far as today propeller turbines with heads up to about 20 m are operating free of trouble, but it is to be considered that my estimate at that time was based on the use of the runner types with very small blade surfaces then employed, and for such types my estimate can today be still considered correct, perhaps even too favorable. That with lower specific speeds (500 to 600) considerably larger blade surfaces can be used whereby the field of application is broadened, no doubt my critics at that time did not know either."

The writer desires in no way to detract in the slightest degree from the importance of Dr. Kaplan's early work in development of the propeller and Kaplan turbines but takes exception to Mr. Karpov's claim for this development as an exclusive European accomplishment. Dr. Kaplan himself frankly admitted his difficulties experienced during this early period, and I might quote from some of his papers as follows.

Writing in the *Wasserkraft-Jahrbuch*, 1925-1926, on "How the Kaplan Turbine Originated," Dr. Kaplan describes his difficulties in a series of tests begun in August, 1921:

"The results of the tests at the laboratory had reached this point when an opportunity offered itself to compare the super-high speed runners in operation with the test results at my turbine laboratory. The appearances mentioned in *Wasserkraft-Jahrbuch* of 1924 then showed themselves, which are called cavitation appearances. The road to the elimination of these appearances was tiresome and connected with many destroyed hopes. Neither I nor my licensed firms knew any solutions as all changes were of no avail. . . . Today, when I review the road of creation of my turbine, I am astonished that the saving idea of the cavitation formation came to me so late, because by this idea all those puzzling appearances with turbines of high speed find their explanation. At that time when the guaranteed tests took place nothing concerning the cause of cavitation was known. In turbine literature there was hardly any mention of it and therefore the bad news kept augmenting which reported an especially large amount of air expulsion and of explosive noises. Neither I nor the engineers could advance any advice. . . . If one examines today a cavitation-free runner, one is surprised why one did not think at once of the simple remedies for eliminating these cavities."

In his description of the modern theories of cavitation phenomena, Mr. Karpov has not mentioned the contributions either of Dr. Thoma or Dr. Spannhake nor the Rogers and Moody paper at the Hydraulic Conference in 1925. In his statement to which the writer has previously called attention regarding model tests, Mr. Karpov is probably referring particularly to cavitation tests. The writer would point out that for several years I. P. Morris Company has been able to avail itself of tests made by its associate company, the Dominion Engineering Works Limited, at the cavitation laboratory of the Shawinigan Water and Power Company at Shawinigan and that through the use of these tests and the study of existing records of plant experience, a large mass of data has been accumulated permitting the reliable design of propeller or Kaplan turbines with either fixed or adjustable blades. The conclusions derived from these data have been quite consistent with the results subsequently obtained at the Holtwood cavitation laboratory. Mr. Karpov has completely ignored notable accomplishments of a number of American engineers working in the propeller turbine field, notably the advances made by Forrest Nagler and the excellent designs and results secured by the S. Morgan Smith Company's engineers in a number of successful installations. The writer has usually found the prominent engineers of Europe willing to give due credit to American engineers for their accomplishments. The writer hopes that claims made on either side of the Atlantic will not be permitted to impair this spirit of fairmindedness and generous recognition of accomplishment.

**James E. Stewart:** Mr. Karpov's paper reaches the logical deduction that propeller type wheels and particularly the Kaplan wheel, will largely supplant the Francis turbine for future low head developments. Accordingly, this discussion will be limited largely to the Kaplan wheel which, except for constant head high load factor loads, probably will be chosen for future installations instead of the fixed blade propeller type.

An interesting point brought out in Mr. Karpov's paper is the academic fact that, other things being equal, the suction drop on the back of the turbine blades is directly proportional to the force applied to the face of the blades. Hence, as brought out in his paper, the avoidance of cavitation depends partly upon keeping down the force per unit of area on the face of the blades; in other words, constructing runner blades with a large total area. However, since the friction loss resulting from large blades is detrimental to efficiency, a nice balance must be struck in determining the best size for the runner blades. No doubt, Mr. Karpov's point that the suction drop on the back of the blade is proportional to the force on the face of the blade, is well known to turbine designers and other students of the subject, but the speaker does not remember hearing or seeing this point brought out in other papers or discussions.

Another interesting point in Mr. Karpov's paper is the fact that for the propeller type turbine the water velocity at the entrance of the draft tube is higher than for the Francis turbine, accompanied by large amounts of water due to low head and large capacity, therefore, the recovery of this larger velocity head necessitates long draft tubes, which in turn are conducive to hunting of the unit. Probably, with the increase in size of American propeller type turbines, the European practise of dividing the draft tube into several sections so as to reduce the size of the moving bodies of water will be followed.

The air-vapor bubble that sometimes forms under certain propeller type wheels is an interesting phenomenon and may be one of the causes of pounding and hunting in certain Francis high specific speed wheels.

Mr. Karpov brings out some interesting thoughts with regard to the use of the propeller type turbine with higher heads. The 76-foot head for the Wettingen development and the 82-106 foot head for the Shannon development are interesting present day developments along that line. If economical and efficient Kaplan turbines can be developed for heads up to say 100 feet, then the Francis turbine can be trusted to economically and efficiently take care of heads from 100 to 1,000 ft and the Pelton wheel for heads higher than 1,000 ft.

It is very probable that we are about to enter a period of extensive low head development with the aid of the propeller type turbines. Not only are there many undeveloped sites where only low head developments can be made economically, but also there are a great number of navigation dams already constructed where the propeller type turbine utilizing syphons or horizontal units may result in very economical developments.

**R. V. Terry:** During the past several years we have been engaged in developing a new type of adjustable vane propeller turbine in which the vanes are adjusted entirely by the flow of water through the turbine, the action being somewhat similar to that of a weather vane. The vanes are pivoted on roller bearings, connected to a dashpot, and provided with means for limiting their angular movement. The vanes are pivoted slightly upstream from their centers of pressure so that the water flow tends at all times to create a relatively small hydraulic moment in the opening direction. This hydraulic moment is balanced by providing a reactive device tending at all times to close the vanes. Experiments have demonstrated that if the vanes are properly proportioned, the reactive moment required to maintain the vanes at the most efficient position will be relatively small and that for a given installation, therefore, for a given speed and diameter of runner, the necessary reactive moment will be substantially constant for varying loads and for varying heads. In other words the vanes of such a runner are automatically adjusted by the water flow to the most efficient angle for any head and for any load within the capacity of the turbine.

In addition to the automatic adjustment during normal operation of the turbine under load, such a runner possesses other interesting features. When the turbine is being started up the vanes assume their maximum pitch position, giving a high starting torque at a small gate opening. As the unit approaches its normal speed the vanes gradually assume the closed position. When the unit is being operated as a synchronous condenser the vanes remain closed.

Outside of the runner the turbine may be of standard construction. No interconnection is required between the runner vanes and the governor which actuates the wicket gates in the customary manner. It is obvious that such an arrangement eliminates much of the equipment necessary for the operation of the usual Kaplan type turbine.

Operation of a unit of this type in connection with a standard governor has demonstrated that the speed regulation is somewhat better than with a fixed blade propeller type. With any appreciable change in either speed, load, or head, the vanes move smoothly to their new position and remain in this position until the conditions are again changed. With small changes in the operating conditions the friction of the mechanism is sufficient to prevent any unnecessary movement of the vanes.

It might be worth while mentioning that we are building a new hydraulic laboratory approximately 36½ ft by 60 ft, three stories high, which will include facilities for studying cavitation of turbine models under head up to 60 ft and draft heads up to 25 ft. The new laboratory will be ready for operation in March 1933.

**F. H. Hollister:** (For discussion see page 188.)

**H. S. Van Patter:** The Canadian Company by which the writer is employed, working in conjunction with a leading United States turbine manufacturer, has designed and built 44 propeller turbines having a total rated capacity of 690,650 hp. These units vary in capacity from 500 to 37,500 hp and operate under heads as high as 68 ft.

The first two of these units, each rated at 28,000 hp under a 56 ft head, were installed in 1922 in the Great Falls Plant of the Manitoba Power Company. Following the Great Falls units, four 30,000 hp turbines under 60 ft head were built for the La Gabelle Plant of the Shawinigan Water & Power Company, and were started early in 1924. While these early turbines have given some trouble from cavitation and pitting, their performance has been distinctly successful, and in all 6 units the original runners are still in service.

Since the initial installation at Great Falls, 4 additional turbines of the same type have been installed. A fifth unit of 32,000 hp rating was installed in the La Gabelle Plant in 1931.

Other notable Canadian installations of propeller type turbines are:

| Power Company | Plant | No. of units | Unit rating | Head |
|---|---|---|---|---|
| Northwestern Pr. Co. | Seven Sisters | 3 | 37,500 hp | 66′ |
| H.E.P.C. of Ont. | Chats Falls | 8 | 28,000 hp | 53′ |
| Churchill River Pr. Co. | Island Falls | 3 | 14,000 hp | 52′ |
| Montreal Island Pr. Co. | Back River | 6 | 12,000 hp | 26′ |

The first three of these plants are equipped with fixed blade propeller runners, and the fourth with propeller runners having manually adjustable blades for operation under heads varying from 17 to 28 ft.

All of the Canadian installations referred to above have runners with six blades. The ratio of blade length to blade spacing near the runner periphery varies from 0.75 to unity, the larger values having been found most suitable for the higher head applications. The area of the runner blades is, in all cases, approximately equal to or greater than the disk area between the runner hub and the runner throat. It is interesting to note that recent Europena designs are very similar in these respects and that, for the more critical high head installations, 6 and even 7 blades per unit are now being used.

With reference to the author's remarks regarding the resistance of various materials to pitting action, it has been the writer's experience that a surface welded with chrome nickel steel or chromium steel, and then ground to a smooth finish is very resistant to pitting action. It has been found that plate steel resists pitting much better than cast steel or cast iron, particularly if the cast material has had the finer grained metal near its surface removed by machining. In the writer's opinion a fairly hard tough material, with as fine a grain structure as possible, is most resistant to pitting.

The author states that "for rough approximations it can be stated that the initial cost of the powerhouse, including hydroelectric machinery, for low head developments, is approximately in inverse ratio to the three-halves power of the specific speed." This would mean that if the specific speed is doubled, the cost would be reduced about 65 per cent. In the writer's opinion a variation in inverse ratio of the square root of the specific speed would be much nearer the mark.

**Adolph J. Ackerman:** In spite of the fact that Mr. Karpov's attainments and activities in the field of arch dams have prevented him from having direct experiences on low head hydroelectric developments, he has acquired a thorough concept of the fundamentals and amplified them by reporting on the results of European research, much of which has had little opportunity to become generally known in this country.

The only suggestion which the writer has to offer relates to extending credit to the original investigators and to some of the periodicals or authorities whose illustrations he has reproduced, so that interested engineers may follow up the original references for further study. Furthermore, in the field of turbine design there are still numerous controversial opinions and it is hoped that Mr. Karpov will increase the value of his paper as an authoritative reference by presenting the names of some of the authorities and scientists whose deductions he has presented, such, as for example, the references to the latest theories on cavitation. By presenting the theory of cavitation as announced by Foettinger in 1925, Mr. Karpov has apparently found that this theory is now generally accepted in Europe, but it would have been interesting if he had also made reference to Dr. Thoma's investigations in which he has analyzed in great detail a blasting action which takes place within the pores of the metal as the result of the collapse of minute bubbles which, by calculation may exert a pressure of a thousand atmospheres in mechanically tearing away small particles of metal. This theory would appear to account more readily also for the fact that rough surfaces, which naturally are more porous, fail more rapidly than do polished ones.

In referring to Fig. 22, showing a cross section of the Vergon powerhouse with inverted syphon, Mr. Karpov draws attention to this as a novel development which "opens quite a number of possibilities for similar developments" and he indicates that this feature should contribute to "development possibilities which were considered economically impossible only a few years ago." Since Mr. Karpov's paper is in certain respects a general indictment of American progress in hydroelectric attainments, the writer is urged to point out that the syphon intake is not as recent or novel as Mr. Karpov infers, having been employed in the Green Island Development of Henry Ford & Son, constructed in 1921 and operating under a head of 18 ft. Furthermore, the idea was mentioned in Daniel W. Mead's "Water Power Engineering," page 512 of the 1920 edition, and in earlier editions, where a plant is described as operating under a head of 31 inches and having an inverted syphon intake almost identical to the one described by Mr. Karpov.

# Safe Harbor Kaplan Turbines

## Design of Setting and Cavitation Limit as Developed at the Holtwood Hydraulic Laboratory

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Non-member Member, A.I.E.E.

***Synopsis.****—The Safe Harbor plant is the first large development in this country to use the Kaplan type of turbine. This paper describes the problems of design and operation which were comprehensively studied by means of model and field tests, with particular regard to the power limits of the turbines as established from a study of cavitation.*

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ONE of the numerous features of the Safe Harbor hydroelectric development of more than usual interest is the application of the Kaplan type of automatically adjustable blade propeller turbine. This type of turbine is used in all of the six units of the initial installation, each rated at 42,500 hp. under a rated head of 55 feet. Safe Harbor is the first installation of Kaplan type turbines of large capacity in America, although they have been used for low head developments in Europe since 1919.

At the time of making the decision to use this type of turbine, the largest Kaplan wheel installed in this country had a capacity of less than 5,000 hp. while the largest wheels then designed, were the 38,000 hp. units since installed at the Ryburg-Schworstadt Plant on the Rhine River in Germany.

While the development of the Kaplan or adjustable runner blade turbine has taken place to the greatest extent in Europe, the development of the propeller turbine, particularly the extension of its field to larger powers and higher heads, has been carried out to the greatest extent in America. The availability of propeller turbines for heads over about 30 feet has been due mainly to American engineers.

Many new and interesting problems arose in connection with these Safe Harbor turbines requiring, as with any pioneering development of this magnitude, an unusual amount of experimental and engineering study involving not only the hydraulic and mechanical design of the plant but affecting the structural and electrical design as well.

The limited experience in this country with propeller type turbines, and more particularly with the adjustable blade turbine, caused the management to feel that certain important operating and engineering information was essential to justify a large expenditure in this comparatively new type of turbine. This feeling was intensified by the fact that the manufacturers had to build wheels considerably larger than had ever been built before. Furthermore, the various manufacturers had each offered for our consideration a number of different designs of this type on which no comparative data as to cavitation limitations were available.

The final design of the power house structure rested upon the decision as to the elevation of the turbine runner. The position of the runner with respect to the tailwater elevation would materially affect the power rating of the turbine as limited by cavitation, and obviously the economics of the power house substructure and excavation could only be determined after the power limits of the various runners submitted for consideration was definitely known.

The absence in this country of a hydraulic testing laboratory in which cavitation tests could be made resulted in the construction of such a laboratory at Holtwood, Pa., adjacent to the Holtwood Hydroelectric Plant.

### REASON FOR KAPLAN UNITS AT SAFE HARBOR

During the early engineering studies an investigation was made of the various types of turbines suitable for the Safe Harbor Development which has a relatively low operating head, limited storage, wide fluctuations in river flow and operating head, and where the peak load value of this plant, as distinguished from a base load plant, is of prime consideration.

Appreciable savings in the cost of power house structures were found possible by using the propeller type of turbine of either the fixed or adjustable blade type. Further savings in the cost of the electrical generators were obtainable with propeller turbines due to their higher speeds‡ permitting the use of smaller and consequently lower cost generators and their direct-connected exciters. The following comparison will clearly show these advantages. The Safe Harbor units rated at 42,500 hp. are spaced 62 feet apart while a high-speed Francis type turbine capable of developing the same horse power under the same head would have to be spaced 70 to 75 feet apart; or for the same unit spacing of 62 feet a Francis turbine would be capable of developing only 30,000 to 35,000 hp. which would obviously require power house structures of appreciably

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‡*Hydraulic and Electrical Possibilities of High-Speed, Low-Head Developments*, A.I.E.E. TRANS., 1931, Jessop and Powel.

larger proportions to obtain the same plant capacity. Again, the speed of the Safe Harbor units is 109.1 r.p.m. whereas the speed of the same capacity Francis turbine, would be only about 60 r.p.m.

The automatically adjustable blade propeller or Kaplan turbine has certain additional advantages over the fixed blade propeller type: a very flat efficiency curve is obtained, it is possible to operate the unit considerably above its normal power rating for short periods of time and without appreciable loss in efficiency, it has materially greater output when operating under reduced heads and is more stable when operating at part load. Due, however, to the additional mechanism required for blade adjustment, the Kaplan turbines are more expensive both in first cost and in maintenance.

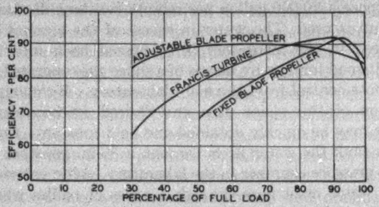

Fig. 1—Comparison Curves for Various Types of Turbines

Safe Harbor unit 42,500 hp., 109.1 r.p.m. (adjustable blade propeller type)
Holtwood unit 20,000 hp., 94.7 r.p.m. (Francis type)
Fixed blade propeller type 40,000 hp., 109.1 r.p.m. 55 ft. head

The relative efficiencies of the Kaplan, the fixed blade propeller and the Francis type turbine are shown in Fig. 1. This curve clearly shows the advantage of the Kaplan turbine for part load operation. The flat shape of the efficiency curve is obtainable due to the fact that the curve shown is the envelope of a series of curves, such as that shown for the fixed blade type, each for a different blade angle. A discussion of the method used in evaluating the power and energy obtainable from the various types and combination of types of units considered, is included in a contemporary paper on Safe Harbor.*

The final decision to use Kaplan turbines in all of the initial units, rather than using one or two Kaplan units and fixed blade propeller turbines for the others, resulted from consideration of the operating requirements of this plant. With a run of river plant such as Safe Harbor where the maximum discharge of the initial six units will be approximately 50,000 cubic feet per second, which flow is available for only about three months in an average year, the plant will obviously operate as a peak load station for the greater part of the time. Such operation involves rapid changes in load. During extreme low flow seasons, when the reservoir will be drawn down on a periodic schedule, a wide variation in the operating head on the plant will be encountered. When the normal river flow is less than the usable flow through the plant, water is valuable for peak service capacity and high operating efficiency at part load is desirable as water thus saved replaces not only steam energy on the system, but increases the capacity value of the plant. High part load efficiencies are particularly important on a system where the spare capacity may be carried at the hydro plants. Furthermore, the Safe Harbor Plant will soon be the point of interconnection of a number of major electrical systems and there will undoubtedly be times when split bus operation will be expedient for considerable periods. With such operation Kaplan turbines are the more economical. Maximum efficiency at full rated load is not essential, as rated output would be required for but short periods during low river flow and at high river flow, when there is an abundance of water, efficiency is not important. Maximum output for short periods and particularly during flood conditions when the back water materially reduces the operating head at the plant is of particular value. Maximum operating economy and flexibility could best be obtained by using turbines all of the Kaplan type. Certain further advantages always accrue through the use of a single size and type of unit in any plant, as it results in a minimum of spare parts to be carried, and minimizes hazards from operation and maintenance.

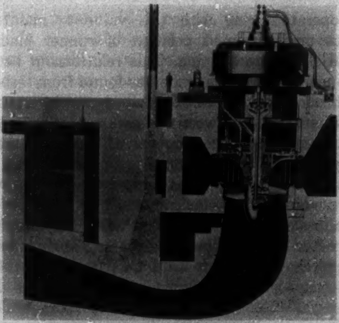

Fig. 2—Cross Section Through Safe Harbor Unit

## Description of Unit

Fig. 2 shows a cut through a Safe Harbor unit. The runner of the turbine is 220 inches in diameter. The runner itself, shown in Fig. 3, has five blades. These blades can be rotated about a horizontal axis from approximately a horizontal position for no-load operation, to an angle of 30 degrees for maximum loads. The blade peripheries and the throat ring are spherically shaped to permit this movement with a minimum of clearance between blades and ring, reducing the amount of leakage from which no energy is obtained.

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*Safe Harbor Project*, by N. B. Higgins, see page 169.

The operating mechanism for changing the blade angle position is shown located in the hub and hollow shafting. Each blade is connected through a link to a main head in the runner hub which is connected by an inner shafting to a large servo-motor located just below the unit thrust bearing. Oil pressure, obtained from the main governor system, is carried to this servo-motor through the Kaplan head (on the top of the generator shaft) from the operating valve shown at the right of the main unit. An actuating rod connects the wicket gate operating ring with this valve to maintain a definite predetermined position of runner blade for each wicket gate opening. This relationship between gate opening and blade angle was found from tests, and is maintained by a specially shaped cam interposed in the actuating rod between the gate operating ring and the runner blade operating valve. This cam may be readily changed for variations in operating head inasmuch as a different relationship is required for each head to maintain best efficiency.

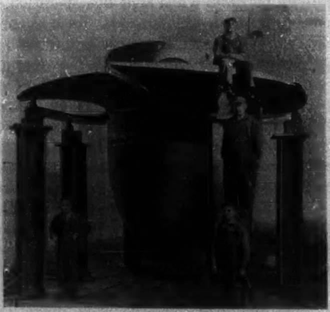

Fig. 3—Kaplan Turbine Runner

The intake section of the unit has a horizontal floor constructed at the same elevation as the river bottom in the forebay. The side walls are parallel and the roof is bell shaped at the entrance. The center line of the turbine was offset from the center line of the intake 2.0 feet for reasons discussed later.

The elbow draft tube has a *V*-shaped roof toward the discharge end, and there is also an appreciable angle of upturn of the horizontal leg to reduce to a minimum the amount of tailrace excavation required.

## Holtwood Hydraulic Laboratory

The Hydraulic Test Laboratory at Holtwood, Pa., was designed for testing model turbines 16 inches in diameter (approximately 1/14 the size of the actual Safe Harbor units) with complete wheel setting and water passages including intake, scroll case, wheel casing and draft tube, under a range in test head varying from 4 to 60 feet, and for purposes of cavitation tests the draft head may be varied from approximately 10 feet pressure head to 10 feet suction head.

The maximum head at the Holtwood Plant is slightly less than 60 feet, but since, for cavitation tests it is necessary to vary the suction head over a wide range while holding the total head the same, it was found impossible to get the desired range of heads by using the available drop between Holtwood forebay and tailrace. A high head tank therefore was built, into which water can be pumped to an elevation approximately 20 feet above the normal Holtwood forebay, for which purpose a 20,000 gallon per minute constant discharge pump is used. The water in excess of the amount required in the laboratory is by-passed back into the Holtwood forebay by means of a sluice gate operated by remote control from the main laboratory. By manipulation of this sluice gate any desired forebay elevation may be quickly obtained and held constant. From this tank the water flows through a 36-in. penstock to the pressure chamber in the laboratory. After entering, the water must pass through a series of baffles which remove whirls and eddies and insures uniform velocity distribution as the water approaches the intake passages of the turbine. The pressure chamber was designed sufficiently large to permit the installation of the complete wheel setting. The water passes from the draft tube into a vacuum chamber, so called, because a vacuum pump connection permits operating this chamber under both positive and negative pressures, required for the cavitation tests. The water finally discharges through a sluice gate at the bottom of the vacuum chamber, or may be allowed to enter the chamber above the vacuum chamber from which a flume carries it to a sharp crested weir. Fig. 4 is an illustration of the laboratory, with the high head tank and pump house in the background and with the weir and its approach channel in the foreground. Fig. 5 is a cross-section of the laboratory showing the various water chambers and the location of the model setting.

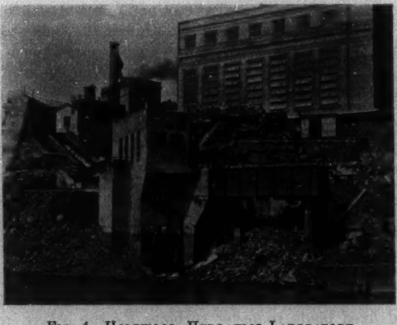

Fig. 4—Holtwood Hydraulic Laboratory

Both the vacuum chamber and the high head tank were designed to permit varying the elevation of the forebay and tailrace over a wide range, yet maintaining the same constant head. Had it not been felt desirable to maintain a constant head for these tests, the high head tank and its accompanying pump could have been omitted.

Because of the wide range required in tailwater elevation, it was impractical regularly to use a weir for measuring the laboratory discharge. A 36-inch by 15-inch Venturi meter was installed in the main penstock for measuring the water flow. The connections to this Venturi meter were brought into the laboratory so that the discharge may be measured in the main laboratory. This Venturi meter was calibrated by Professor C. M. Allen by the "salt velocity" method, and at the same time a calibration was made of the sharp crested weir.

The power developed by the test turbine is absorbed by an electrical dynamometer mounted on the laboratory floor above the pressure chamber, rated at 300 horsepower when used as a generator, but also, for operation as a motor for proposed pump tests designed to develop 225 horsepower. This dynamometer is the first one ever made for vertical mounting and was designed specially for this installation. The electrical power is dissipated in grid resistors located in a separate room at the back of the laboratory.

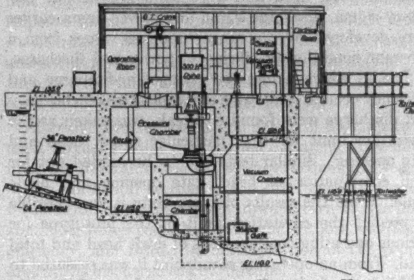

Fig. 5—Longitudinal Section—Holtwood Hydraulic Laboratory

To facilitate the study of cavitation, the laboratory has been laid out to permit visual observation of the water flowing in the draft tube, just below the model runner. This has been accomplished by installing small glass windows in the tube. An observation chamber, provided around the draft tube, affords a point of observation for watching the formation of cavitation and the general behavior of water in the vicinity of the runner. There are two methods of determining the cavitation limit of a turbine. In the first method the presence of cavitation is detected with the eye using a stroboscope, an instrument for cutting the moving wheel from vision through a large part of a revolution so that in effect the eye appears to see the revolving wheel as though standing still. With this instrument, it is possible to observe the formation of the vacuum pockets on the surface of the blade. The water leaving the tips of the blade will have a milky appearance when cavitation is present. There are however, several reasons why it is impractical to accept the visual method alone in determining the operating point at which cavitation begins. The more accurate method used consisted in making a series of tests for varying values of draft head on the runner, while maintaining the speed and the total head the same. A graphical analysis of these test results permits a more exact determination of the point at which this cavitation phenomenon is present.

## CAVITATION LIMIT OF TURBINE

As has been previously stated it is of utmost importance to locate the turbine runner at the proper elevation with respect to the tailrace surface. If any type of waterwheel is located too high above the tailrace, the vacuum formed under the runner blades may cause cavitation. This phenomenon is common even with Francis wheels, and due to the higher velocities present in propeller turbines there is even greater danger of cavitation. The result of cavitation, in addition to serious loss of efficiency, is the destruction of the runner and draft tube by pitting. Pitting is probably due to the combination of erosive and corrosive action. Cavitation starts when the absolute pressure at any point in the water column approaches the vapor pressure of the water, which pressure is, of course, very near absolute vacuum. In most high-speed turbines, either of the Francis or propeller type, the maximum velocity takes place as the water passes through the runner. The greater tendency towards cavitation in a propeller runner is caused by the much greater relative and somewhat greater absolute velocity in combination with smaller blade areas. The exact location of the minimum pressure depends upon the design. If this low pressure falls below the vapor pressure at any point along the blade surface, the water will no longer follow the blade curvature, but will have a tendency to leave the surface of the blade forming a void. The voids will quickly be filled with a mixture of water vapor and air, removed from the adjacent water by "cold" boiling. The surface of separation between the flowing stream and the eddying region left by the separation, may be shown theoretically to be essentially unstable. Hence, sudden breakdowns of the cavities rapidly recur, having the effect of continuing explosions, resulting in intense water hammer action in the pores of the metal. It is this sudden collapse of these many minute bubbles, accompanied by the resulting impact and vibration which is so destructive to the adjacent metal parts. Eventually such action erodes the surface of the runner blades. In addition to this erosion it is probable that oxygen, which is readily released from solutions at very low pressures accumulates along the surface of the runner blades, and attacks the steel surfaces, especially where the metal has been previously attacked by erosion.

Cavitation can be practically eliminated by setting the runner sufficiently below the tailwater level to insure that the minimum pressures along the blade surface are well above the vapor pressure. For economic reasons it is very important to determine accurately the maximum elevation that the runner may be set, to reduce to a minimum the expensive excavation work for the draft tube and tailrace.

Tests on a complete model of the Safe Harbor intake, scroll case, wheel setting, runner, and draft tube were made to determine within very close limits the highest elevation at which the runner could be set without danger of serious cavitation for the maximum turbine power desired. Fig. 6 shows the results of a typical test made in determining the value of draft head at which cavitation starts. The efficiency, power, and discharge of the turbine have been plotted against the coefficient sigma. The term "sigma," first introduced by Professor Thoma of Germany, is derived as follows:

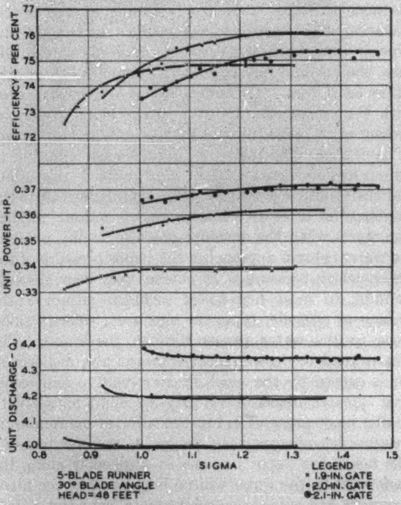

Fig. 6—Typical Cavitation Curves of Test Results

Theoretically, cavitation starts when the absolute pressure on the runner is equal to the vapor pressure of the water, therefore

$$H_B - H_D - \frac{\Sigma V^2}{2g} = H_V \qquad (1)$$

$\frac{V^2}{2g}$ varies directly with $H_T$

Therefore (1) may be written

$$\Sigma = \frac{H_B - H_D - H_V}{H_T} \qquad (2)$$

Where:

$H_B$ = barometric pressure in feet of water at the surface of the tailwater

$H_V$ = vapor pressure of the water

$H_D$ = draft head (elevation of runner minus elevation of water surface in tailrace)

$H_T$ = total net head on the runner

$\frac{V^2}{2g}$ = velocity head at the blade surface

$\Sigma$ = coefficient

The laboratory procedure in determining the cavitation limit for a definite blade angle and gate opening was to start out with a high tailwater elevation and make a series of tests with gradually decreasing tailwater level, maintaining for each series of these tests constant total head and a constant speed. The efficiency-sigma, discharge-sigma and power-sigma curves were developed over a range in sigma values from a constant condition of efficiency, power and discharge, to one in which a material change in discharge and efficiency occurs. The value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit for that particular speed, head and gate opening. Similar tests had to be carried out for each combination of head, gate opening and blade angle. From the results of these tests it was possible to predict the cavitation limit of the prototype for various operating combinations of draft head and total head. From an operating standpoint it was essential to establish the limits of power output for a wide range in both draft head and total head.

### Model Tests of Draft Tube Design

Correlated with the study of the cavitation limits of a turbine, and the economics of determining the proper runner elevation, is the problem of draft tube design. A draft tube which is designed with the shortest vertical section will usually be the least expensive, as a minimum of excavation will be required not only under the power house substructure but also in the tailrace area below the power house.

In the light of European experience, together with theoretical considerations of the water velocities through a Kaplan runner which indicates that the tangential velocity component in the water as it leaves the discharge edges of the runner blades even at part gate, would be relatively small, which tangential velocities would best be recovered in a spiral type of tube; together with due consideration of the somewhat higher construction costs for this type of tube, led to a decision in favor of an elbow type, even though an additional amount of rock excavation was required.

The turbine manufacturers each submitted alternate designs of elbow tubes which were all tested in the Holtwood laboratory with the Safe Harbor model runner, to obtain comparative data on the relative efficiencies and operating characteristics. These tubes differed in the following general features of design:

1. Angle of flare in the vertical section just below the runner.
2. Length of the vertical section (distance between center line of runner and lowest point of the tube).
3. Location and area of the draft tube "throat."
4. Shape and angle of divergence near the discharge end of the horizontal section.

The final design chosen, was determined not only from a consideration of the maximum efficiencies obtained, but also with due regard to the shape of the horsepower efficiency curves, in order to obtain a curve as flat as possible for each blade angle position, thereby eliminating any possibility of instability resulting from sudden changes in load, when the gate opening of the unit might suddenly change without an immediate response of the blade angle mechanism, which latter consideration was felt to be important. A certain amount of actual operating experience available at the time, on the final design chosen was also given due consideration in making the final decision.

After deciding on the general design of the tube to be used, further studies were carried out along three lines: first, the determination of the most economical length of the horizontal section of the tube, second, the determination of the maximum upward turn of this horizontal leg which could be considered without sacrificing efficiency, and third, the determination of the proper area at the discharge end of the tube.

The results of the first of this group of tests indicated that a longer tube than was actually decided upon would have shown higher values of power and efficiency, but it was feared that using a lengthy horizontal section might result in the same regulating difficulties encountered in the use of long penstocks.

The second group of tests on the final tube was made for the purpose of reducing to a minimum the excavation in the tailrace area. A very appreciable amount of excavation was saved by turning this whole tube upward through an angle of 9 degrees without sacrificing either efficiency or power. Tests were made using even greater angles of upturn but the loss in efficiency did not appear to warrant the savings in excavation.

The third group of tests was carried out on modifications of the angle of divergence of this tube as shown in Fig. 9, which also clearly indicates the relative dimensions of the tube, the angle of upturn and the shape of the discharge section. Dimensions shown are for the model tube used in the laboratory. Fig. 10 shows the assembled form work for one of these Safe Harbor draft tubes. A plate steel draft tube liner was used as a form for the upper part of the vertical section.

## Model Tests of Scroll Case Design

A series of scroll case tests was made in the laboratory, before deciding on the final design, in order to determine whether any advantage is realized by offsetting the center line of the runner shaft from the center line of the intake, thereby increasing the cross-sectional area of the scroll and reducing the velocity of the water. The results indicate that if, for the unit spacing used at Safe Harbor, a speed ring with a relatively large diameter were used a very noticeable saving in efficiency and power could be obtained. If, however, the fixed guide vanes of the speed ring were of narrow proportions and the speed ring of smaller diameter, there was no improvement found in either efficiency or power.

The scroll case of the Safe Harbor turbines were, however, designed eccentric even though the overall diameter of the speed ring was relatively small, this decision being made to give a maximum of flexibility in the design of the wheel settings for all future units for this plant.

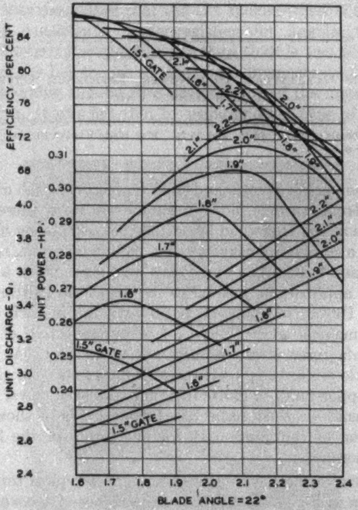

Fig. 7—Typical Efficiency Curves of Test Results

## Power and Efficiency Tests

All turbine manufacturers were asked to submit with their guarantees of power and efficiency, the test results obtained from a model of the runner which they were submitting for consideration at the Safe Harbor Plant and on which these guarantees were based, as it was felt that a comparison of these test results obtained from the same size models was of greater value than a comparison of the actual guarantees. Unfortunately, however, these tests were of course made in the laboratories of the different manufacturers and it was later realized that a fair comparison of such tests could not be made. This, it should be pointed out, is no reflection on the laboratories but merely an honest recognition of the difficulties encountered in obtaining an absolute calibration in special commercial laboratories of this type. Such a comparison was further complicated by the fact that certain manufacturers were unable to make tests on a gross head basis, as the laboratory was not designed to permit the use of a model intake and scroll case.

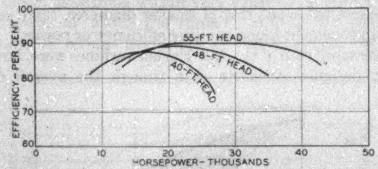

FIG. 8—GUARANTEED HORSEPOWER EFFICIENCY CURVES—SAFE HARBOR UNIT

Safe Harbor development guaranteed horsepower efficiency curves. Gross heads of 40 ft., 48 ft., and 55 ft. Five blade Kaplan turbine; speed 109.1 r.p.m.

Comparative power and efficiency tests on each of the numerous turbine designs submitted were therefore made at the Holtwood laboratory, all tests being made with a complete turbine setting, including intake, scroll case and draft tube. These tests were made under a test head approximately equal to the field head existing at Safe Harbor of about 50 to 55 feet, and in each case was made in the presence of a representative of the manufacturer whose runner was under test. At the completion of these tests the manufacturers were given the opportunity to revise their guarantees of power and efficiency on their respective turbines. Fig. 8 shows a portion of the guarantees for one group of the Safe Harbor units.

A curve sheet giving the results of a typical test, is shown in Fig. 7. The range in the values of $\Phi$ covered, corresponds to a variation in head of from 32 to 60 feet, although the actual testing was done under a constant head and varying speeds. Tests were made at various blade angles to develop an envelope curve representing the maximum efficiency obtainable for the proper operating relationship between blade angle and the wicket gates, which relationship is maintained on the actual units as previously described by means of a cam in the blade operating mechanism.

These cams were designed from the data obtained on the model runners, and it has been found from actual field tests that only minor reshaping of the cam was necessary to obtain the best operating efficiencies.

During these power and efficiency tests, it was found that on certain gate openings a vortex was formed near the bottom of the deflector or the hub of the runner. This vortex was readily observed through the windows of the model draft tube, and was found to occur over a wide range of test conditions, although not in the normal limits of field operation. It was feared however that this vortex might appear in the Safe Harbor turbines although it has not been detected up to this date. This same phenomenon is undoubtedly the cause of hydraulic instability at part loads of a fixed blade type of turbine, which frequently results in unsteady operating conditions and serious difficulties when attempting to synchronize.

## FIELD TESTS

To insure that the units are properly adjusted and are operating to give the best possible efficiency, numerous field tests and inspections were planned. A certain amount of cavitation is probably permissible since the steel blades of the turbine will resist a considerable amount of shock and it was decided to operate the units slightly beyond the point where cavitation started in the laboratory, and carefully study the effect on the runner blades and draft tube.

During the first few months of operation the turbines were carefully inspected about every two weeks. Now that the plant has been in operation some time, these inspections occur about every six weeks on each unit. It has been found that on certain portions of the runner blades, paint was removed. There is a small area on both the top and bottom surface at the leading edge near the periphery, which seemed to be subject to local cavitation. Very small hollows and reversals in curvature attracted cavitation, and eventually pitting took place. The original design of the leading edge called for very slight rounding of the corners only, with very little reduction in thickness of the blade. Probably this local cavitation was caused by the impact of water impinging on the blunt nose and forming eddies, and a low pressure area just back of the leading edge. By slightly reshaping the leading edge so that it was sharper, and making a

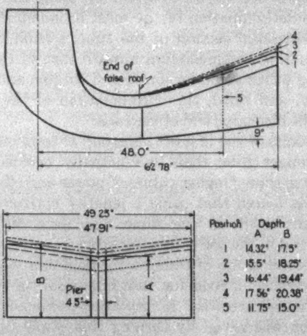

FIG. 9—VARIOUS DRAFT TUBE MODIFICATIONS STUDIED

very gradual transition from the nose to original blade surface from six to eight inches back from the leading edge, this local cavitation was largely eliminated. This area will probably always be susceptible to cavitation, and consequently, it is of the greatest importance to have a very smooth surface, free from reversals in curvature. One unit was held at a power output limit well below the point where cavitation started on the model. The paint erosion on this unit was less than paint erosion on the other units, but the local pitting mentioned above was of about the same magnitude, and in the same place.

Fig. 10—Form Work of No. 7 Unit at Safe Harbor

On the underside of the blades near the trailing edge, an area has been attacked by a very slight cavitation of a magnitude sufficient to remove the paint, but as yet there is no indication of pitting. It is interesting to note that rust has covered these areas in spite of the cavitation.

To establish the most efficient relationship between gate opening and blade angle, it is not necessary to measure the actual efficiency or discharge, and it was decided to establish this relationship by the use of an index method. Seven piezometers were therefore installed at various points in the scroll case and on the wheel setting during the construction of the plant. At the time of the turbine efficiency tests these piezometers will be calibrated and a meter will ultimately be installed to integrate as well as indicate the discharge through the turbines. It is proposed to have a meter on each unit and a totalizing meter will be located in the control room to indicate the total discharge through the plant.

The usual methods of testing hydroelectric units used in this country have been found inadequate on most low-head developments where large quantities of water are to be measured, due to the shortness of the approach passages to the unit. In Europe, current meters have been used for a number of years in making efficiency tests, and have been found particularly adapted for use on low-head developments. A number of turbine efficiency tests has been made in this country with current meters, but on such tests, only a few meters were employed, and the results have usually been of doubtful accuracy. It was decided at Safe Harbor to follow the European method of making current meter tests and to employ the Ott meter so generally used abroad.

One difficulty encountered in making current meter measurements is the time required to traverse properly the area of the metering section. It was found that a large number of metering points would be necessary for each horizontal traverse. Twenty-seven current meters were therefore purchased of the spoked-wheel type and all mounted in the same horizontal plane on a rack made up of stream line rods. This rack can be lowered in the gate slots to any desired elevation for obtaining a vertical traverse.

It was recognized that the Ott spoked-wheel current meter consistently under-registers for angular flow. The metering section, at the gate slots is just at the end of the bell-mouth so that there obviously would be considerable angular flow near the top of the metering section. It was felt that by using another type of current meter which gave a greater degree of under-registration for angular flow it would be possible, by proper calibration, to determine the actual angle of the stream flow from the difference in velocities obtained by these two types of meters, and true velocity could be computed. For this purpose Dr. Ott of Germany recommended a conical screw propeller meter which under-registers to an even greater degree with angular flow than the spoked-wheel type. It was found that the difference between the indicated velocities of these two types of meters increased uniformly with an increase in the angle of flow so that for a given difference

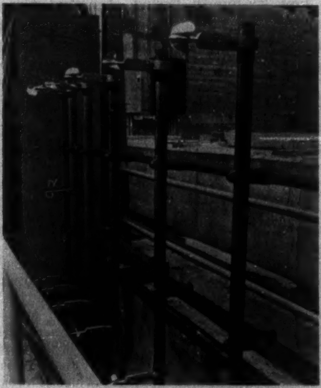

Fig. 11—Current Meter Rack with Meters in Place

in observed velocity on the two types of meters the true angle of flow was readily determined and a proper correction could be applied to obtain the true velocities passing the metering section.

Twenty-seven additional conical screw propeller current meters were therefore purchased and mounted on the same current meter rack six feet above the spoked-wheel meters. Fig. 11 shows a portion of one of these racks with the two types of meters in place.

## CONCLUSIONS

The test program as carried out in coordination with the plant design has resulted in numerous improvements in operating performance, saving in construction costs, and has permitted a more complete study of the behavior of these units. Such a program eliminated to a large degree the necessity of relying too greatly on the very limited field experience available. No little part of the success of this program is due to the efforts of the engineers of the two turbine manufacturers who, to a greater extent than ever before in the hydroelectric development of America, cooperated to build turbines of identical hydraulic and mechanical design wherein practically all replaceable parts are interchangeable.

The first six-month period of actual performance indicates that the prediction of the cavitation limits for the turbines based on the laboratory model test results is reasonably close, although a considerably longer period will be necessary to establish definitely a close correlation between laboratory and field results.

Turbine efficiency acceptance tests have not yet been completed.

## Discussion

**E. Brown:** The account of experimental work carried out at the Holtwood Laboratory shows that operating companies are fully convinced of the importance of testing of turbine models, especially in connection with projects of such magnitude as the Safe Harbor development. The conditions of operation at Safe Harbor are fundamentally different from those found in Canadian projects, in which many propeller turbines of output up to 37,500 hp have been installed in the past few years for heads as high as 65 ft. The reasons for the adoption of the Kaplan type of wheel at Safe Harbor, are made clear by the authors, and as the preliminary experimental work has evidently been carried out with great thoroughness it will be interesting to relate the experiences of actual operation with the expectations based on tests of models.

The authors point out the importance of a study of the efficiency, unit power, and unit quantity, in their relation to the cavitation factor, as determining the elevation of the runner in relation to the tailrace—a factor which obviously influences greatly the economics of any project.

Some typical curves for a head of 48 ft are shown in Fig. 6. It would appear, however, that these must refer to some condition not paralleled in the large units, because the highest efficiency shown is only 76 per cent, whereas Fig. 8 shows expected guaranteed efficiencies for the S. Morgan Smith wheels as ranging from 80 per cent to 89 per cent for that head. Possibly Fig. 6 refers to some speed other than normal. The curves in Fig. 6 show large differences between the values of sigma at which the efficiency begins to decrease, and the unit quantity to increase. Thus for the gate opening 2.1 in., the efficiency begins to decrease at sigma 1.3, whereas the unit quantity does not increase until sigma = 1.1. The points of increase or decrease are not well defined, and this is frequently the case in such tests. The authors do not state whether the draft head was measured to the elevation of the trailing tips of the runner blades, or to some other elevation of the runner, so that the distance from trailing tips to tailrace level for any given value of sigma is uncertain. A difference of 0.2 in the value of sigma, as noted above, corresponds however to a difference of 9.6 ft in suction head, when the operating head is 48 ft. Even if the so-called "breaks" in the curve were estimated to be closer together than as stated above,—so that the sigma difference is only 0.1—the corresponding difference in suction head would be 4.8 ft. This is a large amount, representing 10 per cent of the operating head in these tests. Possibly the form of the curves for tests giving higher efficiencies showed sharper breaks at sigma values, more nearly equal than those referred to above. The authors' statement that "the value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit for that particular speed, head and gate opening" would seem to imply much closer agreement between sigma values than that shown in Fig. 6. Some additional information on this point would be welcome.

The authors state further that in cavitation tests it is necessary to vary the suction head over a wide range *while holding the total head constant*, and special pumps were installed to control the headrace level to fulfill this condition. The writer is not aware that the necessity for constant head has been fully established, and it would add greatly to the value of the paper if some definite data could be given to show the differences in efficiency, unit power, and unit quantity obtained at a given sigma: (*a*) under constant head; (*b*) under a head controlled only by changing tailwater level. The large units themselves are apparently expected to operate under variable head, say from 40 ft to 55 ft as shown in Fig. 8, and in practise the variations in tailwater level are frequently greater than in headwater level. The conditions are of course governed by many factors, and particularly by considerations of peak-load operation in which the level of the headrace pond may be drawn down considerably in a short time. Curves of the type shown in Fig. 6 have been obtained by the writer in experimental work similar to that described by the authors, but with approximately constant headrace level, and have been used successfully in connection with the installation of large propeller turbines having fixed blades. It would seem, however, that the authors regard constancy of head as of great importance. It would be interesting to know how it has been established that results of cavitation tests made at constant head are more directly applicable to conditions existing in an actual plant in which the head varies, than are the results of tests made at the same values of sigma when these are obtained by varying the tailwater level.

It may be well to draw attention to the fact that extremely low pressures do not release *air* from the water, if by air is meant oxygen and nitrogen in the proportions found in the atmosphere. The solubility of oxygen in water is greater than that of nitrogen, and the gases released are relatively richer in oxygen than is the atmosphere from which those gases are derived. The possibility of this greater oxygen content being favorable to certain actions which might contribute to pitting should not be overlooked.

The authors refer to the difficulty in measuring the quantity of water used in low head plants owing to the shortness of the water passages, and their experiences in the use of the European method of metering will be welcomed. The writer first used the Ott method some years ago under similar conditions, and believes that it offers many advantages.

It is hoped that when experience in operation of the Safe Harbor plant is sufficiently extended, the authors will present the results in their relation to the expectations based on the Holtwood tests, and thus contribute greatly to our knowledge of hydroelectric practise at low heads.

**J. A. Peck:** The writer is one of those who, by virtue of lack of personal contact with the interesting phenomena of cavitation, is not very clear as to some aspects of the investigations referred to in the paragraphs on this subject. Was the efficiency test method, for determining the point at which cavitation begins, considered more accurate because the efficiency break occurred before the milky condition of the water became visible by means of the stroboscope, or because the break occurred at a value of sigma which was part of a relatively wide range of sigma values, over which the cloudiness was visible but showed no critical condition? Were the limiting values of sigma chosen at the break for the sake of efficiency maintenance or was there an expectation, at the time of these investigations, that a cavitation condition, existing at sigma values where no adverse effect on efficiency was apparent, would not be seriously destructive to the runner blade? What means were employed to isolate the phenomenon of the efficiency break so that it is positively attributable to the cavitation rather than to some other coincidental factor, such as a crisis in the flow conditions within the particular type of draft tube in use?

The writer had hoped for a more complete treatment of the use of flow index methods, but realizes that a great deal of work can be expended in analysis of such investigations and trusts that they may be the subject of a later paper.

In the choice of draft tubes it is remarked that, while a longer tube than that chosen would have shown higher values of power and efficiency, it was feared that regulating difficulties might result. This recalls similar doubts in regard to the great horizontal length of the tube installed at the Bellows Falls plant of the New England Power Association. The choice here was limited to a long and narrow tube by the fact that the entire tube and most of the wheel setting was to be excavated from ledge, so that each tube became a special form of concrete lined tunnel. The horizontal length from the shaft center line to the mouth of the tube was 100 feet.

This tube was investigated in tests made at the S. Morgan Smith Company in 1927 and described in the 1930 report on Draft Tube Tests by the Hydraulic Power Committee of National Electric Light Association. The model has a throat diameter of 16 inches, while the prototype diameter is 14 feet, 5½ inches, a ratio of 1 to 10.83. According to the system of proportions adopted for the test report referred to, using the throat diameter as unity, this tube has a depth of 2.99 and a horizontal length of 6.88. By scaling the Safe Harbor tube in Fig. 9, it appears that the longest tubes have a depth of 2.05 and a horizontal length of 3.85.

In general, these model tests agree with the authors' results, that the longer tube yields greater capacity and higher efficiency and that the mouth may be raised without sacrificing either. In elevating the mouth of the tube, however, it was found that, if the slope began too near the bottom of the curved elbow, a decided loss was incurred. The tube adopted retained a level floor about half way from the elbow to the mouth, then sloped abruptly upward at an angle of about 11 degrees.

This plant has been in operation for over three years and is one of the automatic frequency regulation centers. As far as effects traceable to the draft tube are concerned, regulation has been entirely normal. The salt velocity test, made by Professor C. M. Allen of Worcester Polytechnic Institute in 1929, showed a maximum net efficiency of 93 per cent.

**L. B. Stirling and J. B. MacPhail:** This paper is a valuable addition to the literature of tests on hydraulic models. The work which it describes must have saved a great deal of uncertainty in matters which are beyond computation, and one may expect that experience in operation of the units will again show the value of this method of determining the most suitable equipment for new conditions. The designers of the model plant are to be congratulated on the extent of the facilities which they have provided for this work.

The writers have been engaged, under direction, on some similar work on propeller runners at the testing plant of the Shawinigan Water and Power Company, at Shawinigan Falls. The plant was built some nine years ago, before sigma had been heard of, but it has been found suitable for certain cavitation and efficiency tests, the results of which have afterwards been confirmed in operation.

The curves in Fig. 6 do not show the sharp break which is supposed to indicate definite cavitation, and it would be desirable to know at what points on the sigma curves the cavitation limits were considered to occur. It might be mentioned that the models tested at the Shawinigan plant showed little drooping, even with values of sigma as low as 0.52, but this, of course, is largely a characteristic of the runner.

We would like to know also, whether the possible occurrence of draft tube pitting was examined by paint tests. There is believed to be a good relation between pitting of a painted surface in a model draft tube, and erosion of concrete on the full size installation; that is, a model which shows no pitting of such paint will probably show no erosion of concrete on natural scale. This relation has proved to be correct in two cases at least, and it may be provisionally assumed to be true in other cases where the models have not actually been built in full size.

The relation between the efficiency of a model turbine and that of a homologous unit of a larger size is given in a paper presented before a meeting of the American Society of Civil Engineers in 1925 by Mr. Moody. It would be interesting to know whether the manufacturers base their guarantees exactly upon this formula or, if not, what margin they allow in order to protect themselves against the possibility of their turbines not operating exactly as calculated.

The writers were very interested to note that the Safe Harbor turbines are to be tested by means of current meters and it is to be hoped that the details of these tests will be made available to the profession. The Shawinigan Water and Power Company has been making turbine tests with current meters for several years and the results have been quite satisfactory. This method of testing has advantages over other methods now in use in that it interferes very slightly with the normal operation of a plant and the amount of preparatory work required is very small.

The authors of this paper are to be congratulated on the work which they have done and the manner in which it is presented in this paper. It is to be hoped that the study of turbine characteristics will be continued at this plant, as it appears that the most rapid advance of the art of turbine design will be made through the use of this and other similar plants.

**R. E. B. Sharp:** During the cavitation tests of some of the models tested at the Holtwood Laboratory, the writer observed, through the openings in the draft tube, that cavitation often existed along the trailing portion of the runner blades nearest the hub. The writer thinks he is correct in saying that this condition could be seen before the cavitation limit, as indicated by runner performance, was reached, but would like Mr. Davis's corroboration on this point. The cavity formed at this part of the runner was doubtless caused by the necessarily increased blade thickness near the hub, and by fillets which are necessary from stress considerations, where the blades join the hub. This cavitation appeared to be continuous, and to extend over an appreciable portion of the blade upstream from the trailing edge. The testing of the runners at and above the cavitation limit produced pitting on the blades, but although the cavitation was actually visible at this part of the blade, no pitting was observed on the blade surfaces.

The cavitation test data clearly demonstrate that with a given value of sigma and a given amount of power developed, the tendency to cavitate increases with phi, or in other words, with the velocity of the blade surface. Nevertheless, the writer would like to find a clear explanation and reason for actual cavitation being more effective in producing pitting at a high blade velocity than where such actual cavitation exists, but with low blade velocity.

An installation in Canada furnishes an interesting example of the ability of a turbine to operate without serious pitting, with a value of sigma so low as to result undoubtedly in the formation of continuous cavitation without sufficient pressure to cause the collapse of the cavities. Fig. 1 shows points representing the installations noted, plotted between sigma as the ordinate and specific speed as the abscissa. A line has been drawn along several of the lower points as representing roughly the limit in sigma for the usual modern propeller runner designs.

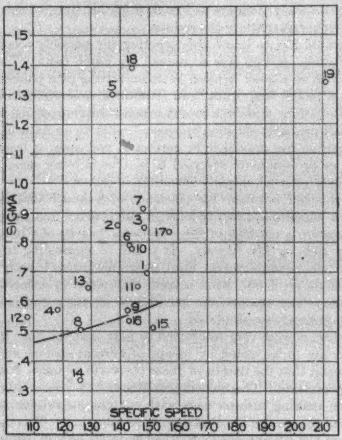

Fig. 1

| No. installation | Hp. | Hd. | No. installation | Hp. | Hd. |
|---|---|---|---|---|---|
| 1 Safe Harbor | 42,000 | 55 | 10 Hydro El. Pr. Co. | 5,000 | 36 |
| 2 Beebee Island | 5,000 | 30 | 11 Chat Falls | 28,000 | 53 |
| 3 Beebee Island | 5,700 | 30 | 12 Maribondo | 5,000 | 59 |
| 4 Dolby | 3,900 | 48 | 13 La Gabelle | 32,000 | 60 |
| 5 Anson | 1,500 | 20 | 14 St. Albans | 4.000 | 64 |
| 6 Slave Falls | 500 | 30 | 15 Manitoba | 28,000 | 56 |
| 7 Slave Falls | 12,000 | 30 | 16 Mixnitz | 12,150 | 64.4 |
| 8 Churchill | 14,000 | 56 | 17 Ryburg | 37,700 | 38.7 |
| 9 Seven Sisters | 37,500 | 66 | 18 Lilla Edet | 11,200 | 21.3 |
|  |  |  | 19 Vargon | 15,200 | 14.1 |

Admittedly, this method of plotting these points is not altogether sound, as the value of phi and the blade area is not considered. The Canadian installation mentioned is point No. 14, with a value of sigma of 0.334, where for this value of specific speed (126) the curve of minimum sigma values passes through sigma equals 0.503. No information as to the efficiency developed by this turbine is available. However, it has operated for more than three years without noticeable pitting, under a total head of 64 ft. This is a propeller type, six-blade runner, stepped from the same model as the runners in the 28,000 hp Manitoba units (point No. 15), and the runner in this turbine replaced a runner (incidentally of foreign design) which did not stand up at all against the pitting action.

In this case, there was no choice, of course, but to accept the limitations as to diameter, the existing value of sigma and the specific speed. Naturally, for a new development such a value of sigma would not be considered. Nevertheless, the performance of this replace runner indicates that the carrying of the sigma curves to values far below the initial break in the performance curves might show unexpected results. In this case continuity of flow is undoubtedly completely destroyed for some distance below the runner, with attendant loss of efficiency as represented by the actual loss in head. On the other hand, the water probably is entirely clear of a portion of the blades with some attendant reduction in friction loss.

The authors state that "the value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit." The true cavitation limit, however, is the point at which any one of the curves, quantity, power or efficiency, starts to break, or in other words, to be affected by cavitation.

It is to be hoped that at some time in the future cavitation tests will be made at Safe Harbor to determine the relation between the break in sigma on the large turbines with that on the model. This would, of course, require varying the tailwater and headwater levels, and a large number of runs under constant head with definite gate and blade positions. But on the other hand, the data obtained would be, it is believed, unique, and of great value.

**H. S. Van Patter:** The writer has read with interest the reasons for the selection of Kaplan turbines for the Safe Harbor Plant, and the description of the Holtwood Hydraulic Laboratory and of the tests conducted therein to determine the most suitable design of turbine casing and draft tube for the Safe Harbor units. The officials and engineers of the Pennsylvania Water and Power Company deserve much credit for undertaking the expense and labor involved in such research work.

From personal experience, the writer can appreciate the immense value of research work of this character. The Shawinigan Water and Power Company has had a similar testing plant in operation at Shawinigan Falls, Quebec, since 1924, and the writer has had the pleasure of working with the engineers of this company in connection with the tests conducted therein. To a considerable extent, these tests dealt with the phenomena of cavitation and pitting of propeller type turbines and determination of the most suitable designs for use under heads of 50 feet and higher. A considerable number of runners and various designs of guide vanes, throat rings, and draft tubes have been tested.

The testing procedure used in recent years has been quite similar to that outlined by Messrs. Davis and Spaulding, *i. e.*, by determining the power, efficiency and discharge at various gate openings for a range of sigma values. It was felt, however, that entire reliance should not be placed on this method only, as the proper interpretation of the results so obtained is, to a considerable extent, a matter of opinion without a mass of data on the correlation between model tests and field results. Consequently a technique has been developed for studying the actual effects of cavitation on the surfaces of the runner blades, throat ring and draft tube by the use of surface coatings which are unaffected under normal conditions of operation but which are readily removed by pitting action. Very good results have been obtained by using nickel plating on the bronze runner blades and two coats of different colored paint on the surrounding cast iron surfaces.

Why was it considered necessary to hold the total head constant when varying the suction head and has the decision in this respect been confirmed by test results? In other words, have the authors' tests shown that the cavitation point is affected by variations in total head?

The authors state that in determining the safe value of sigma, the value at which the efficiency and discharge curves break is taken as the limit. Referring to Fig. 6, for best gate opening 2.0 the efficiency curve breaks at sigma 1.25 and the discharge at 1.05. Is this variation characteristic? If so, which value is used?

The writer would like to point out that the comparison of unit spacing required for Francis and Kaplan turbines for the Safe Harbor units would not apply in the case of a base load plant where either type of unit would be operated normally at best efficiency point. In this case there would be little if any difference between the two types.

**F. H. Hollister:** (For discussion see page 188.)

**G. W. Spaulding and L. M. Davis:** Professor E. Brown raises several important questions. Fig. 6 refers to a test at normal speed but at maximum blade angle, consequently the model efficiency is rather low. The guaranteed efficiency for these conditions is only 80.5 per cent.

It is a peculiarity of the Safe Harbor turbine design that the break in the efficiency curve occurs at a higher value of sigma than the break in the unit quantity curve. Other models tested in the Holtwood laboratory show a sharper efficiency break and both unit quantity and efficiency breaking at the same values of sigma. The discrepancy in unit quantity and efficiency breaks caused considerable controversy before the decision was finally reached to use the break in the unit quantity curve. As a final check on this decision one unit was operated on power limits derived from the break in the efficiency curve for ten months and the progress of paint erosion compared with the other units operating at the higher power limits. As there was no noticeable difference in the rate or magnitude of paint erosion on this unit in comparison with the other units it was placed on the higher power limits. There is little doubt that cavitation occurs at higher sigma values than the break in the efficiency curve. However, unless it reduces the efficiency or attacks the metal parts it is not objectionable.

The draft head was measured from the center line of the runner.

It is known that, theoretically, the variation of the ratio of diameter of runner to head affects the critical value of sigma. Since the extent of this effect was uncertain the Holtwood laboratory was designed to permit constant head testing. After making tests in which the head was varied from 35 ft to 50 ft it was concluded that the effect on the cavitation limit, within the range of tests, was not apparent.

Mr. J. A. Peck's questions have been partially discussed in the preceding paragraphs. As he suggested the milky or cloudy condition of the water gradually increases over a wide range of sigma. The first cloudiness is visible at much higher values of sigma than the break in the efficiency curve.

At the time of the Safe Harbor model tests, there was some thought given to paint erosion tests on the throat ring and draft tube as mentioned by Messrs. L. B. Stirling, J. B. MacPhail and H. S. Van Patter. However, after the cavitation tests were completed it was noted that the shop coat of red lead was still in perfect condition on the model draft tube. This was taken as excellent evidence that no pitting would occur in the draft tube. The Safe Harbor units have been carefully inspected from time to time and after over a year's operation there is no indication of pitting on the throat ring or draft tube.

Mr. R. E. B. Sharp's observation of visual evidences of cavitation occurring along the trailing portion of the runner blades nearest the hub is correct. Since ordinarily the first trace of pitting on a propeller runner occurs on the bottom surface near the trailing edge and the periphery we were indeed surprised to note that the first visual evidences of cavitation occurred near the hub. The only explanation that has been advanced is the one suggested by Mr. Sharp, that cavitation is caused by the water not being able to close in smoothly after passing the thick fillet near the hub and the collapse of these cavities thus formed occurs below the runner in the draft tube, thus the blades near the hub are untouched.

# The Principle of Condenser Discharge
## Applied to Central Station Control Problems

BY F. H. GULLIKSEN*
Associate, A.I.E.E.

***Synopsis.***—*The paper describes the principle of a resistor coupled condenser discharge circuit as a means for indicating the rate of change of an electrical potential. The application of this circuit to an impulse relay which may be used in connection with quick response excitation regulating equipment is outlined.*

*The principle of operation of an electronic voltage regulator is referred to, and an oscillogram is given indicating the definite anti-hunting action which can be obtained with the condenser discharge circuit as an anti-hunting means.*

*A thermionic type automatic synchronizer, which requires only 5 voltamperes per potential transformer, is described in detail. The paper treats the method by which, for any frequency difference within limits of present operating practise, the synchronizer will cause the closing coil of the circuit breaker to be energized in advance of synchronism by a time equal to that required to close the breaker, so that, assuming the frequency difference between the two systems remains constant during the short time required to close the breaker, the breaker contacts will always be closed at the instant of zero voltage phase displacement.*

*A formula has been derived whereby the synchronizer "advance" may be calculated for various frequency differences when the constants of the thermionic circuits are known, and the results obtained with the thermionic type automatic synchronizer in a generating station with propeller type water wheels are described.*

### INTRODUCTION

DURING the past few years the application of electronic tubes has been a topic of increasing interest to electrical engineers. Electronic devices are now rapidly supplanting electro-mechanical apparatus in a multiplicity of applications, and the versatile electronic tube is put to work in new control devices, performing duties which could not have been accomplished with the electro-mechanical devices previously available.

The combination of a condenser discharge circuit and an electronic tube provides the fundamental elements for indicating the rate of change and the direction of change of an electrical potential. The purpose of this paper is to outline the fundamental principle of the condenser discharge circuit, and to describe its application in connection with three specific electronic control devices, namely, an impulse relay, an electronic voltage regulator, and an automatic synchronizer.

### FUNDAMENTAL CONDENSER DISCHARGE CIRCUIT

The fundamental circuit consists of a condenser 1 connected in series with a resistor 2, which is connected in the grid circuit of tube 3, as shown in Fig. 1. The current through tube 3, for a definite plate voltage $E_P$ depends upon the voltage $E_g$ of the grid bias battery 4, and the characteristic curve for a tube will be as shown in Fig. 2. If a voltage $E_1$ is applied with a polarity as shown in Fig. 1 a charging current will flow through resistor 2 to the condenser. This charging current will produce a voltage drop across the resistor with a polarity as indicated in Fig. 1. Consequently the bias on the grid of tube 3 will become more positive and the current through tube 3 will increase. After a definite time, dependent upon the time constant $RC$ of the discharge circuit, the condenser will be fully charged, and the charging current, and consequently the voltage drop across the resistor will become zero, so that the current through tube 3 will come back to the original value as determined by the grid bias battery. If now voltage $E_1$ is varied we obtain a voltage drop across resistor 2 which is essentially proportional to the rate of change of $E_1$, and the polarity of this voltage drop will reverse if the direction of change of $E_1$ is reversed. The important features of this circuit are primarily that the current through tube 3 is not affected by the magnitude of voltage $E_1$, but is only affected by the rate of change of $E_1$, and further, that since resistor 2 may be several megohms, only a minute amount of control power is needed.

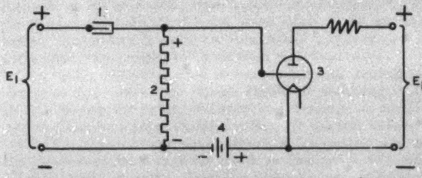

FIG. 1—FUNDAMENTAL CONDENSER DISCHARGE CIRCUIT

### IMPULSE RELAY

A possible application for the condenser discharge circuit is in connection with an impulse relay for quick response excitation voltage regulators. With this type of equipment it is highly desirable to provide additional field forcing by shunting out all resistance in series with the exciter fields, if a sudden drop in regulated voltage should occur. It is imperative that the quick response excitation element operates with a minimum time delay, and it is desirable to arrange the quick response element separate from the main control element so that separate adjustment may be obtained, and so that calibration of

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the main control element does not affect the adjustment of the quick response element.

The various types of electro-mechanical voltage regulators for quick response excitation now on the market are equipped with an additional pair of contacts which will close if the regulated voltage drops for example 5 per cent below the normal value. It is obvious that the time between the drop in regulated voltage and the closure of the quick response contacts depends upon the position of the moving element of the regulator at the instant of voltage disturbance, so that the time interval will be increased if the regulator element were in the "lower" position, *i.e.*, the regulated voltage was slightly too high when the load disturbance occurred. By using an electronic type quick response element the response of the regulating equipment would be independent of the voltage conditions previous to the load disturbance, and would only depend upon the magnitude of the voltage drop.

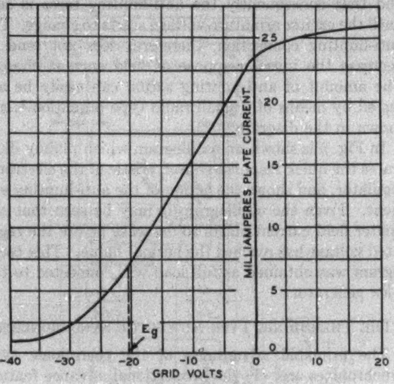

Fig. 2—Tube Characteristic

A schematic diagram of the impulse relay circuit is shown in Fig. 3. A transformer 1 is connected to the regulated voltage source and feeds into the full wave rectifier tube 2. The direct-current voltage across resistor 3 will, therefore, be proportional to the regulated voltage. An amplifier tube 4 is connected to resistor 3 in such a manner that the plate current of tube 4 does not change if the regulated voltage changes slowly. This is obtained by selecting the location of the resistor tap so that any change in tube plate voltage is compensated for by a proportional change in grid bias voltage. This condition is determined by the amplification constant of the tube. A resistor 5 and a condensor 6 are connected in a discharge circuit to the grid of tube 4 so that for decreasing regulated voltage the grid of tube 4 will become more negative and consequently the voltage drop across resistor 7 will decrease due to the decreased plate current of tube 4. When the voltage drop across resistor 7 decreases, a voltage drop will obtain across resistor 8 due to the discharging action of condenser 9. The polarity of the voltage drop across resistor 8 will be as indicated in the diagram, so that the grid voltage of the glow tube 10 becomes more positive and causes tube 10 to break down and energize the quick response shunting contactor coil 11. Contactor 11 remains closed until the direct-current supply voltage for tube 10 is disconnected by means of the contacts 13 of the field current limiting relay. The d-c supply for tube 10 is supplied from the 250 volts station bus through the voltage divider 12.

The response of this equipment compares favorably with the electro-mechanical quick response elements at their best and the response does not, as previously stated, depend upon the voltage conditions immediately before the fault occurred.

## Electronic Voltage Regulators

The condenser discharge circuit is an important feature of electronic type voltage regulators which have recently been brought on the market. These regulators are now available for direct-current and alternating-current generator voltage regulation. The electronic regulator for d-c generators applies high vacuum tubes as power tubes and has a field current regulating range of 0.75 amp. The electronic voltage regulator for a-c generators applies glow tubes as power tubes and in its present design can handle a maximum field current of 8 amperes. The important features of these electronic type regulators are the high sensitivity of ± 0.2 per cent, the simplicity of operation, and the extremely fast response characteristic.

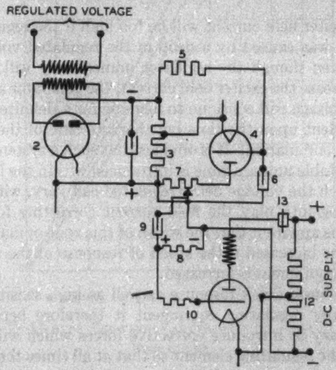

Fig. 3—Impulse Relay

The fast response characteristic is made possible through the application of the condenser discharge circuit as an anti-hunting means.

Due to the inductive lag of the field windings of exciters and generators, the generator armature voltage will always be lagging in relation to the exciter field current, if the exciter field current is undergoing a change as a result of regulator action. If no anti-hunting means are supplied, the generator armature voltage will not have reached the normal value when the exciter field current attains the value corresponding to the new generator load conditions. Consequently, when the generator voltage is brought back to the normal value the exciter field current will be too high if the regulator action was caused by a drop in the regulated voltage, and even though the regulator immediately will start to decrease the exciter field current, the generator armature voltage will continue to increase for a definite time dependent upon the time lag characteristic of the machine combination. It is obvious that such a system will be unstable unless a zone is introduced within the limits of which the voltage being regulated can vary, without bringing into play the field current correcting forces, and it is apparent that the width of this zone of inaction must be increased if the speed of response of the regulating equipment is increased.

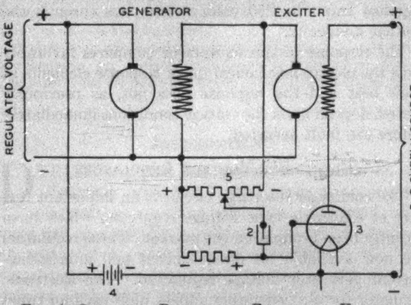

Fig. 4—Schematic Diagram of Electronic Voltage Regulator

To obtain quick response as well as high sensitivity with any regulating equipment it therefore becomes necessary to introduce corrective forces which will act upon the regulating element so that at all times the rate of generator voltage change is proportional to the error in regulated voltage.

A simplified schematic diagram of the electronic voltage regulator for d-c generators is shown in Fig. 4. The exciter field winding is connected in series with the electronic tube 3 which is supplied with plate voltage from a separate d-c source. The generator voltage is bucked by means of battery 4 so that increasing generator voltage will increase the negative bias on the grid of tube 3 and consequently decrease the exciter field current. The anti-hunting action is obtained through the condenser discharge circuit consisting of resistor 1 and condenser 2, which are connected in series across the exciter armature. The action of the anti-hunting circuit is such that when the exciter armature voltage is decreasing the polarity of the voltage drop across resistor 1 will be as indicated in the diagram, and will, therefore, provide a positive bias on the grid of tube 3. This positive bias counteracts the original negative bias resulting from the initial increase in regulated voltage, and consequently tends to stabilize the equipment. It should be noted that the amount of anti-hunting force is proportional to the rate of change of exciter armature voltage, and that consequently the anti-hunting force is zero until the exciter armature voltage starts to change. The anti-hunting connection, therefore, does not tend to decrease the initial response of field current change. The amount of anti-hunting action can easily be adjusted by means of a small radio type potentiometer 5 shown in the diagram.

In Fig. 5 is shown an oscillogram which plainly illustrates the quick response characteristic of the electronic regulator, and shows the action of the anti-hunting element. From the oscillogram it may be seen that the exciter field current starts to decrease before the regulated voltage has reached the normal value. This oscillogram was obtained as full load was connected to the 5-kw generator.

## The Thermionic Type Automatic Synchronizer

The principal advantages of the thermionic type synchronizer are: (1) the proportional advance feature which provides means for energizing the breaker closing coil at a point in advance of synchronism proportional to the frequency difference, and, (2) the low voltampere burden of 5 voltamperes per potential transformer. Considering the steadily increasing use of condenser bushing potential devices with capacity limited to from 15 to 20 voltamperes it would seem that there is a definite need for a low capacity automatic synchronizing device, and the thermionic type automatic synchronizer should therefore find wide application.

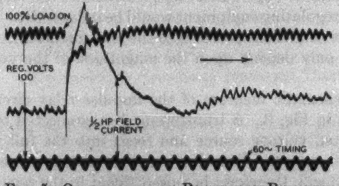

Fig. 5—Oscillogram of Regulator Response

The principle of operation of the thermionic synchronizer was described in a previous article,* and the reader is referred to this article for a complete description of the design and the operation of the equipment. In this paper, therefore, only a brief outline of the prin-

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*The *Electric Journal*, July 1931, pages 421-423.

ciple of operation is given, while the application of the condenser discharge principle to the proportional advance circuit is more thoroughly described.

The schematic diagram of the thermionic synchronizer is shown in Fig. 6. Two telephone type relays II and III are controlled by means of thermionic tubes so that relay III will operate at a fixed point in advance of synchronism, the closing characteristic being independent of the frequency difference; while relay II, the advance relay, will operate at a point in advance of synchronism proportional to the frequency difference. As shown in Fig. 6, an interlock is arranged between the two relays so that relay IV, which is energizing the breaker closing relay, is closed only if relay III is operated before relay II is closed.

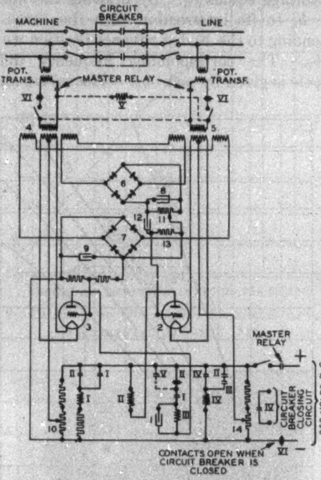

Fig. 6—Schematic Diagram of Thermionic Type Automatic Synchronizer

### Lock Out Relay III

A thermionic tube, indicated as 3 in Fig. 6 is connected in series with the coil of relay III across a 250-volt d-c supply circuit. The grid bias for tube 3 is supplied from the rectified beat voltage obtained from rectox 7. When the phase angle between the system voltages is 180 deg a high negative bias is, therefore, applied to the grid, and the tube current consequently is zero. When the phase angle is reduced, the negative bias is decreased and the current through relay III is increased. At a definite phase angle displacement between the system voltages the current through the coil of relay III will be high enough to operate the relay. By adjusting potentiometer 10 the operating point of relay III can be located at any position between zero deg and 40 deg phase angle displacement. The purpose of tube 3 and associated equipment is consequently only to provide definite closure of relay III at any predetermined phase angle displacement.

### Advance Feature

The proportional advance characteristic of relay II is obtained through the action of the condenser discharge circuit consisting of condenser 12, resistor 13 and rectox 6. The d-c output voltage of rectox 6 will be pulsating at a rate proportional to the frequency difference between the two systems to be paralleled. The voltage across the condenser 12 is equal to the output voltage of rectox 6, when the frequency difference is zero, and can be expressed by $e = E \cos \Phi$ where $E$ is the maximum voltage when the phase angle displacement $\alpha$ is 180 degrees and $\Phi$ is determined so that

$$\Phi = \frac{\pi}{2} \text{ when } \alpha = 0, \text{ and } \Phi = 0 \text{ when } \alpha = 180 = \pi.$$

The angle $\Phi$ may be expressed by $\Phi = \Delta f \pi t$ where $\Delta f$ is the frequency difference in cycles and $t$ is the time in seconds required for angle $\Phi$ to change from zero to $\Phi$. If there is a definite frequency difference $\Delta f$ between the two systems and the phase angle displacement $\alpha$ is changing from 180 deg towards zero, then the

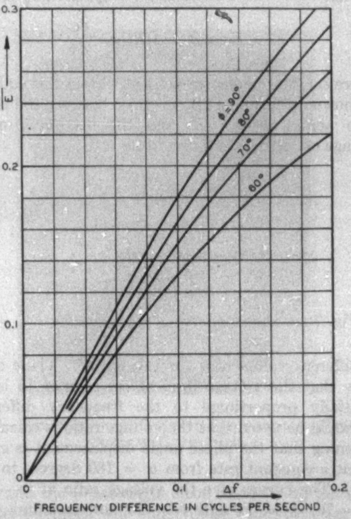

Fig. 7—Curves Showing Values of $\frac{e_R}{E}$ for Varying Frequency

Difference at various values of angle

voltage across the terminals of rectox 6 and the voltage across condenser 12 will be decreasing, but the voltage across condenser 12 will be higher than the rectox voltage by an amount dependent upon the time constant $RC$ of the discharge circuit and the frequency difference $\Delta f$. The discharge current from the condenser will produce a voltage drop across resistor 13 so that the potential on the grid of tube 2 will become less negative. When the phase angle displacement between the system voltages is increasing from zero to 180 deg the polarity of the voltage drop across the resistor will be reversed. Considering the performance of the automatic synchronizer the conditions for decreasing phase angle displacement only are of interest, since no relay action can take place when the phase angle displacement is increasing.

By using the nomenclature previously outlined the voltages in circuit 8-12-13 can be expressed by

$$e_c = E \cos \Phi - \Delta f RC\pi \frac{de_c}{d\Phi}$$

where $e_c$ is the condenser voltage. From this equation, as shown in the appendix, the ratio between the voltage drop across resistor $R$, and the maximum output voltage of rectox 6 is found to be

$$\frac{e_{\mathrm{R}}}{E} = \frac{\Delta f RC\pi}{(\Delta f RC\pi)^2 + 1}$$

$$\left[ \Delta f RC\pi \cos\Phi - \sin\Phi - \Delta f RC\pi e^{\frac{-\Phi}{\Delta f RC\pi}} \right]$$

In Fig. 7 are shown curves giving $\frac{e_{\mathrm{R}}}{E}$ for $RC = 0.58$ at different values of $\Phi$ for varying $\Delta f$. These curves show that the voltage drop across resistor 13 is substantially proportional to the frequency difference. It should be noted that the voltage ratio is calculated, assuming that the phase angle displacement is changing at a constant rate from $\alpha = 180$ degrees to $\alpha =$ zero. The curves give the voltage ratio at $\Phi = 60$; $\Phi = 70$; $\Phi = 80$ and $\Phi = 90$, corresponding to 60, 40, 20 deg and zero phase angle advance respectively.

In addition to the bias potential obtained from resistor 13, a constant negative bias is applied to the grid of tube 2 by means of potentiometer 14 and a varying negative bias is obtained from rectox 7. Potentiometer 14 is so adjusted that the negative grid bias obtained from the potentiometer is equal to $E_g$ in Fig. 2, corresponding to the operating current of relay II, consequently relay II will operate and close its contacts at zero phase angle displacement when the frequency difference is zero. For any definite frequency difference the closing point of relay II will correspond to that advanced phase angle position where the voltage given by the curves in Fig. 7 is equal to the voltage obtained from rectox 7.

In Fig. 8 are shown the curves from Fig. 7 and the voltage across rectox 7 plotted according to the same voltage scale. By means of these curves the frequency difference can be determined which will give relay closure at a definite advanced phase angle by drawing rectangle $b_1$—$b_2$—$b_3$—$b_4$. In order to determine the frequency difference at which relay II will close at a 40-deg phase angle, the line $b_1$—$b_2$ is located at 40 degrees advance. This gives rectox voltage $b_1$—$b_2$. As previously stated relay II will operate when the rectox voltage equals $e_{\mathrm{R}}$. By drawing the horizontal line $b_2$—$b_3$ to its intersection with the curve for $e_{\mathrm{R}}$ corresponding to the 40 deg advance position we obtain point $b_3$. The corresponding frequency difference 0.146 cycle is given by point $b_4$. The curves shown in Fig. 8 give the maximum value of $e_{\mathrm{R}}$, and consequently give maximum advance, corresponding to approximately 27 deg per 0.1 cycle frequency difference. This would be suitable for a circuit breaker having 0.75 second closing time. In order to adjust the equipment to suit circuit breakers with shorter closing time the $e_{\mathrm{R}}$ voltages are adjusted downwards by means of potentiometer 11 of Fig. 6. The calculated advance curve given in Fig. 9 shows how close the calculated data check with results obtained by actual tests.

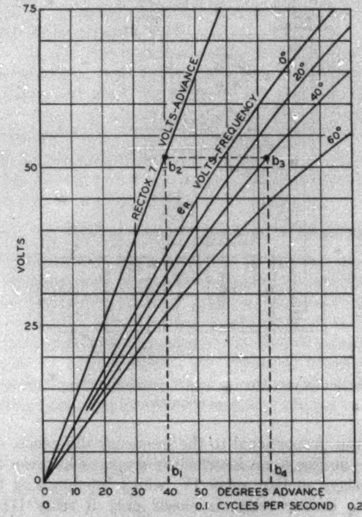

Fig. 8—Curves for Advance Calculation

## VOLTAGE ERROR

For line voltage differences within 15 per cent of normal voltage the synchronizer operates practically without error so long as a definite frequency difference

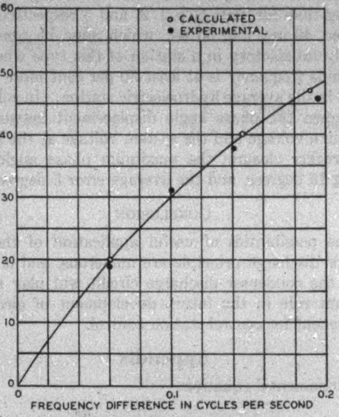

FIG. 9—CALCULATED CURVE FOR MAXIMUM ADVANCE. EXPERIMENTAL ADVANCE DATA

FIG. 10—THE THERMIONIC AUTOMATIC SYNCHRONIZER

exists between the two sources to be connected. One reason for this is*, that the beat voltage at 30-deg phase angle displacement between the system voltages does not change appreciably, and the grid bias voltages of tubes 2 and 3 in Fig. 6, therefore, will remain unchanged. Furthermore a 15 per cent change in filament voltage does not affect the tube operation since the plate current is considerably below the maximum filament emission at rated voltage. When a voltage difference is present, there will be an equalizing current flowing between the two systems even if the breaker is closed at exactly zero phase angle displacement. This equalizing current will be proportional to the voltage difference at zero phase angle displacement, and will be proportional to the beat voltage at any other phase angle displacement. Since the beat voltage at 5-deg phase angle displacement is only 12 per cent higher than the beat voltage at zero phase angle displacement if a 15 per cent voltage difference is present, it will be realized that a few degrees error in synchronizer performance will have a negligible effect on the paralleling operation.

In generating stations, synchronizing is usually accomplished at a frequency difference exceeding 1/10 cycle, and the phase angle error due to a 15 per cent voltage difference will under these conditions not exceed 4 degrees, which of course is quite satisfactory.

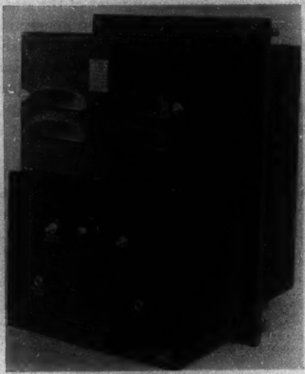

FIG. 11—THE ELECTRONIC VOLTAGE REGULATOR FOR DIRECT-CURRENT GENERATORS

When the synchronizer is applied to connect two systems the frequency difference will usually be below 1/10 cycle, and if the two systems are already tied together at some other point the frequency difference will be zero. To obtain breaker closure if a voltage difference is present under above conditions, it is necessary to widen the synchronizing zone. Recalibrated in this manner the synchronizer will perform perfectly at the maximum voltage difference for which the device was recalibrated; but will close too early if the voltage difference is zero. The amount of early closure measured in degrees will be equal to one-half of the maximum voltage difference in volts, referring to 110 volts as normal voltage.

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*See A.I.E.E. TRANS., Vol. 48, page 1185, Fig. 2.

## TUBE LIFE

The operating life of the thermionic tubes is in excess of 3,000 hours. Assuming that the synchronizer is in service during 1 hour each day, the useful life of the tubes would be approximately 8 years. It is apparent from Fig. 6 that in order to obtain breaker closure both relays II and III must operate. No faulty synchronizing can, therefore, take place due to tube failure.

## FIELD TESTS

Through the courtesy of the Kentucky Utilities Corporation a series of tests was made at the generating station located at Dam No. 7, Kentucky River. This station is equipped with three generators 850 kva, 150 rpm, driven by vertical propeller type waterwheels. Due to the low inertia of the units, and due to the inherent characteristic of the hydraulic equipment the frequency of these generators at no load is very erratic. The automatic switching equipment of the station is so arranged that any one of the three generating units could be started up either by means of push-button control in the station or by means of supervisory control. During the tests, as recorded in Table I, the time required for the various units to get up to synchronous speed was observed as well as the total synchronizing time from the start of a unit until breaker closure. In column 5 of Table I is given the time during which the synchronizer was in actual control, and the performance of the synchronizer should be judged by these data. It may be seen that the average synchronizing time for units Nos. 1, 2, and 3 respectively was 51 sec, 40 sec, and 60 sec, which must be considered highly satisfactory in a station of this type where the machine frequency is at least 50 per cent more erratic than in the average hydroelectric station. In column 6 is shown the phase angle displacement between the machine voltage and the system voltage at the instant of breaker closure; the maximum phase angle error being 15 degrees, and the average error 5 degrees.

TABLE I

| 1<br>Test No. | 2<br>Unit No. | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| 1 | 1 | 0.40 | 1.17 | 0.37 | 0 |
| 2 | 1 | 0.40 | 4.30 | 3.50 | 5 |
| 3 | 1 | 0.41 | 1.03 | 0.22 | 5 |
| 4 | 1 | 0.39 | 5.07 | 4.28 | 15 |
| 5 | 1 | 0.41 | 1.14 | 0.33 | 0 |
| 6 | 1 | 0.40 | 1.07 | 0.27 | 0 |
| 7 | 1 | 0.39 | 0.47 | 0.08 | 10 |
| 8 | 1 | 0.38 | 1.04 | 0.26 | 5 |
| 9 | 1 | 0.40 | 0.59 | 0.19 | 5 |
| 10 | 1 | 0.39 | 1.09 | 0.30 | 0 |
| 11 | 1 | 0.39 | 0.51 | 0.12 | 5 |
| 12 | 1 | 0.39 | 0.46 | 0.07 | 0 |
| 13 | 1 | 0.39 | 1.51 | 1.12 | 10 |
| 14 | 1 | 0.37 | 0.51 | 0.14 | 5 |
| 15 | 1 | 0.40 | 0.49 | 0.09 | 0 |
| 16 | 1 | 0.38 | 1.51 | 0.13 | 5 |
| 17 | 2 | 1.00 | 1.34 | 0.34 | 5 |
| 18 | 2 | 0.57 | 2.10 | 1.13 | 0 |
| 19 | 2 | 0.57 | 1.04 | 0.07 | 10 |
| 20 | 2 | 0.55 | 1.03 | 0.08 | 5 |
| 21 | 2 | 0.58 | 1.17 | 0.19 | 10 |
| 22 | 2 | 0.54 | 1.13 | 0.19 | 5 |
| 23 | 2 | 0.59 | 3.47 | 2.48 | 0 |
| 24 | 2 | 0.57 | 1.02 | 0.05 | 0 |
| 25 | 2 | 0.57 | 1.10 | 0.13 | 15 |
| 26 | 2 | 0.58 | 3.31 | 2.33 | 10 |
| 27 | 3 | 0.57 | 2.34 | 1.37 | 0 |
| 28 | 3 | 1.00 | 1.40 | 0.40 | 0 |
| 29 | 3 | 1.02 | 1.15 | 0.13 | 5 |
| 30 | 3 | 0.59 | 1.59 | 1.00 | 0 |
| 31 | 3 | 1.02 | 1.59 | 0.57 | 0 |
| 32 | 3 | 0.50 | 1.18 | 0.28 | 5 |
| 33 | 3 | 1.01 | 2.20 | 1.19 | 5 |
| 34 | 3 | 1.03 | 3.48 | 2.45 | 10 |
| 35 | 3 | 1.02 | 1.46 | 0.44 | 10 |

3 = Time in min. and seconds required for unit to come up to speed.
4 = Total synchronizing time from start of unit until breaker closure.
5 = Time during which synchronizer was connected.
6 = Degrees phase displacement at moment of breaker closure.

## CONCLUSION

The possibilities of useful application of the condenser discharge principle are numerous, and it is felt that the condenser discharge circuit will play an important role in the future development of electronic equipment for central station control.

# Appendix

Fundamental equation:

$$e_c = E\cos\Phi - \Delta f RC\pi \frac{de_c}{d\Phi} \tag{1}$$

$$\text{Introducing} \begin{cases} e_c = uv; \dfrac{de_c}{d\Phi} = u\dfrac{de_c}{d\Phi} + v\dfrac{du}{d\Phi} \\ G = \Delta f \pi RC \end{cases}$$

Gives:

$$uv = E\cos\Phi - \mathrm{G}\left[u\frac{de_c}{d\Phi} + v\frac{du}{d\Phi}\right]$$

From this equation is found:

$$u = e^{\frac{-\Phi}{G}}$$

$$v = \frac{E}{\mathrm{G}\left(1 + \frac{1}{G^2}\right)} e^{\frac{\Phi}{G}} \left[\frac{\cos\Phi}{G} + \sin\Phi\right] + C_1$$

Consequently:

$$e_c = uv = c_1 e^{\frac{-\Phi}{G}} + \frac{E}{\mathrm{G}\left(1 + \frac{1}{G^2}\right)} \left[\frac{\cos\Phi}{G} + \sin\Phi\right] \tag{2}$$

constant $c_1$ to be determined so that $e_c = E$ when $\Phi = 0$

which gives $C_1 = \dfrac{EG^2}{G^2 + 1}$

Substituting $c_1$ in equation (2) gives

$$e_c = \frac{EG^2}{G^2 + 1} e^{\frac{-\Phi}{G}} + \frac{E}{\mathrm{G}\left(1 + \frac{1}{G^2}\right)} \left[\frac{\cos\Phi}{G} + \sin\Phi\right]$$

From equation (1) is obtained since

$$e_R = \Delta fRC\pi \frac{de_c}{d\Phi}$$

$$\frac{e_R}{E} = \cos\Phi - \frac{e_c}{E}$$

$$\frac{e_R}{E} = \cos\Phi - \frac{G^2}{G^2+1} e^{\frac{-\Phi}{G}} - \frac{G}{G^2+1}\left[\frac{\cos\Phi}{G} + \sin\Phi\right]$$

$$= \frac{G}{G^2+1}\left[G\cos\Phi - \sin\Phi - Ge^{\frac{-\Phi}{G}}\right]$$

Substituting $G = \Delta fRC\pi$ gives final equation

$$\frac{e_R}{E} = \frac{\Delta fRC\pi}{(\Delta fRC\pi)^2 + 1}$$

$$\left[\Delta fRC\pi \cos\Phi - \sin\Phi - \Delta fRC\pi\, e^{\frac{-\Phi}{G}}\right] \tag{3}$$

This equation may be used in calculating the advance curves as shown in the main body of the paper.

# Direct Selection System of Supervisory Control

BY M. E. REAGAN*
Member, A.I.E.E.

MODERN supervisory control systems were designed and placed in permanent operation first approximately eleven years ago; they were of the "code" type and operated over three wires. In 1924, the "synchronous" systems were introduced. Recently, a demand for higher speed led to the development of a "direct selection" system which eliminates sequence stepping or counting chains. All systems operate over line wires of telephone size. Modern arrangements use two or four wires depending on the number of operations to be performed.

In order to obain an idea of the three general principles involved, first imagine a row of small control switches and associated indicating lamps in a dispatcher's office and a corresponding row of power switches or circuit breaker in some remote substation. Regardless of the number of operations to be performed, only two or four line wires are available first to select the proper switch and then to operate it, meanwhile obtaining a lamp indication of its open or closed position.

Synchronous selecting systems shift both ends of the line wires simultaneously from point to point. Thus, the lines are connected first to No. 1 control switch in the office and No. 1 switch in the substation; then they are disconnected concurrently at both ends and reconnected to No. 2 control switch in the office and No. 2 circuit breaker in the distant substation. This action is repeated until the wires reach the breaker to be operated. Here the stepping action ceases and the line wires are used for direct control. The breaker may be opened or closed at the will of the dispatcher and corresponding lamp signals give him the indication of its position. Thus it may be seen that some time is consumed by connecting the line wires to breakers on which no operation is wanted. Such stepping means usually operate at approximately ten steps per second so that 5 seconds' time would be required to reach the 50th breaker before any operation could be accomplished.

Code selecting systems operate on a different principle. The plan of selection of one type is first to switch the substation end of the line wire circuits from breaker to breaker until the desired one is reached, by a definite number of impulses sent from the dispatcher's office. The substation equipment then sends an equal number of checking impulses to the office to step that end of the line wire circuits from control switch to control switch until the corresponding one is attained. Again, the breaker may be opened and closed as desired by the dispatcher and at the same time he gets a lamp indication of its status. Here, also, some time is consumed in the selection. In the two-wire all-relay type, the total selecting time is approximately double that taken by the synchronous system since the check-back takes as long as the selection.

Direct selection systems are practically instantaneous inasmuch as the mode of operation consists of sending a single direct-acting impulse from a control switch at the dispatching office direct to the related circuit breaker at the substation. Instead of switching the line wires by stepping them from point to point, they are connected instantly to the control switch and corresponding circuit breaker by means of circuits which can receive only electric currents having definite combinations of polarities. Each breaker, therefore, has a definite combination to which it alone responds so that a single impulse of the proper combination immediately selects that particular breaker. No time is required or consumed in connecting the line wires to points where they are not to be used. To insure the accuracy of the selection, however, a checking impulse is returned from the breaker to the dispatcher's office. The time of choosing the breaker and obtaining the verification of its correctness is the same for each breaker.

The control equipment in the dispatcher's office for each circuit breaker is the same as used on practically all previous supervisory systems and consists of:

1 point selection lamp which indicates that the proper point has been selected before operation is attempted.

1 disagreement lamp which indicates an automatic operation in the substation.

1 "trip" supervisory lamp which lights when device is open.

1 "close" supervisory lamp which lights when device is closed.

1 control key whose position determines the operation of "close" or "trip."

1 point selection button which connects the selecting combinations of polarities to the line wires.

There is also common equipment consisting of:

1 operation control button which sends the "close" or "trip" operating impulse to the substation.

1 release button for resetting equipment and stopping an alarm.

Besides the relay equipment and that just listed, the control office is equipped with one 48-volt storage battery, charging facilities, and line wire protectors. The substation equipment consists of corresponding relay equipment, interposing relays, one 48-volt storage battery, charging facilities, and line wire protectors.

The direct-selection system is based upon the fundamental method of relay valve operation in which current through the relay in one direction operates it and current is blocked from the relay in the other direction. In the four-wire classification, the pushbutton in the dispatcher's office functions to connect battery polarities

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., Jan. 23-27, 1933.*

to the line wires and to operate the register relays at the substation. The receiving relay group consists of eight unidirectional relay circuits; for these, ordinary neutral relays with copper oxide rectifier valves are employed in order that time-proved devices may be utilized in a manner such that they perform their usual functions.

The four-wire system is based also upon the employment of individual point selection relays at both ends of the line wires. These relays are particularly useful at the substation to prevent interference between supervisory indications originated at the same instant by the simultaneous tripping of several circuit breakers. Furthermore, they assure the dispatcher that the desired breaker has been selected and connected to the line wires before he attempts operation.

Briefly, an operation is performed by first pressing the point-selection button and waiting until the point-selection lamp glows, indicating that the desired equipment is connected to the line wires ready to be operated; this requires about 0.4 sec. The control key then is turned to the desired operation (in the case of breakers, "close" or "trip") after which pressing the operation control key causes the substation equipment to change position; an indication of the new position then comes to the dispatcher automatically.

To give a more detailed account of this procedure a short outline of the circuit functions is given. In the normal condition of the line circuit both ends are held in readiness for operation over a circuit through the line wires and relays at each end in series. As soon as an operation is initiated from the dispatcher's end or a supervisory indication originated from the substation, this normal circuit is opened in order to disconnect the starting relay at the end which is to act as the receiving end in the succeeding function. By this means interference is prevented effectively when both ends attempt to initiate a selection at the same time.

Assuming that the dispatcher originates the selection, a single impulse is transmitted from the office to the substation after the normal circuit has been opened. A different combination of positive and negative battery potential is applied to the four-line wires for each of 50 points, thereby energizing the selection relay of the desired point at the substation, through intermediate receiving relays.

When the point selection relay at the substation is energized, it sends a second single impulse back to the dispatcher's office where this impulse causes the operation of the proper point selecting relay. The polarity combination of the return impulse is different from that of the first impulse in order to provide double assurance that the proper relay has been selected at the substation. Simultaneously with the operation of the point-selection relay at the office, the associated point-selection lamp is caused to glow, thus informing the dispatcher that the selection is completed.

If, by reason of induced currents from adjacent power line disturbances, a point-selection relay other than the desired one has been selected at the substation, a polarity combination will be returned to the office which will cause the glowing of a point-selection lamp not associated with the originating point. Also, if for the same reason the correct point-selection relay has been operated at the substation, but the return impulse fails to energize the correct point-selection relay at the office, the point-selection lamp of the originating point will not glow, but that of another point. Therefore, if the dispatcher sees the point-selection lamp of the selected point glow, he is assured that the established connection is correct; if he doesn't, he resets and reselects.

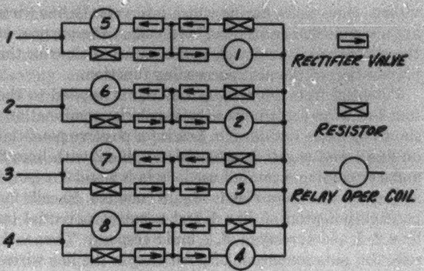

Fig. 1—Schematic Diagram of Receiving Relay Circuits for a Four-Wire System

The point-selection relays remain energized and two of the line wires are connected through to the individual point equipment for control and supervision, while the remaining two line wires are utilized to maintain the connection until the selection key is restored to its original position. An alarm may be provided to insure the release of the equipment by the dispatcher.

If an automatic operation occurring at the substation is to transmit the corresponding supervisory indication to the office, a single impulse is sent to the office, causing the operation of the corresponding point-selection relay. The operation of the office relay sends a checking impulse to the associated point-selection relay at the substation. The control and supervisory line wires then are connected through and the supervisory indication transmitted to the office. The connection is maintained until the supervisory lamps at the office actually have changed to agree with the new position of the supervised device, whereupon the connection is released automatically and the circuit returns to its normal rest condition.

Means are provided at the substation for effecting a proper succession of supervisory signals, if two or more supervised devices at the substation change their positions at the same time. This guarding arrangement is effective even if several devices change their positions at exactly the same instant. This is accomplished by interlocked relay circuits in which only one relay may be operated at a time.

Brief intervals are introduced between the normal rest condition and the first impulse, between this first impulse and the return impulse and between the return impulse and the completion of the control and supervisory connections, during which intervals the line wires are disconnected entirely at both ends. The purpose of these intervals is to give each end sufficient time for the preparation of the next succeeding function.

Potential from the 48-volt battery is applied to the four-line wires according to the 50 polarity combinations shown in Table I. Code No. 1 calls for positive potential on line 1 and negative potentials on line 2 with lines 3 and 4 remaining open (not used); relays 1 and 6 respond as may be seen from Fig. 1. Again code No. 50 calls for positive potential on line 1 and negative potential on lines 2, 3, and 4; relays 1, 6, 7, and 8 respond. Thus each selection puts some code of polarities on the line wires; hence the name "Polaricode" has been applied. Two-line wires only are used for twelve of the 50 codes; three only are used for 24 codes, while all four are used on the remaining fourteen codes.

A diagram of the receiving relays with their associated register circuit is shown in Fig. 2. As already mentioned, the selection of No. 1 breaker calls for the energizing of relays 1 and 6; at the substation end, these are known as S1 and S6. When the contacts of S1 and S6 are closed, relays S11 and S16 are energized. Relay S11 in turn energizes relay S26 over "break" contacts of relays S12, S13, and S14. This completes the selection circuit for register relay No. 1 from battery positive through "break" contacts of S15, "make" contacts of S16, "break" contacts of S17 and S18, "make" contact of S26, and No. 1 relay coil to negative battery. The other register relays are energized by similar apparatus circuits. Thus any one of fifty breakers can be selected by a single impulse over four-line wires. The time for any one of the fifty selections, including check-back, is approximately 0.4 sec.

TABLE I—POLARITY COMBINATIONS

| Code No. | Lines | | | | Relays | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | + | − | | | 1 | ... | ... | ... | ... | 6 | ... | ... |
| 2 | + | | − | | 1 | ... | ... | ... | ... | ... | 7 | ... |
| 3 | + | | | − | 1 | ... | ... | ... | ... | ... | ... | 8 |
| 4 | | + | − | | ... | 2 | ... | ... | ... | ... | 7 | ... |
| 5 | | + | | − | ... | 2 | ... | ... | ... | ... | ... | 8 |
| 6 | | | + | − | ... | ... | 3 | ... | ... | ... | ... | 8 |
| 7 | + | + | − | | 1 | 2 | ... | ... | ... | ... | 7 | ... |
| 8 | + | + | | − | 1 | 2 | ... | ... | ... | ... | ... | 8 |
| 9 | + | | + | − | 1 | ... | 3 | ... | ... | ... | ... | 8 |
| 10 | | + | + | − | ... | 2 | 3 | ... | ... | ... | ... | 8 |
| 11 | + | − | + | | 1 | ... | 3 | ... | ... | 6 | ... | ... |
| 12 | + | − | | + | 1 | ... | ... | 4 | ... | 6 | ... | ... |
| 13 | + | | − | + | 1 | ... | ... | 4 | ... | ... | 7 | ... |
| 14 | | + | − | + | ... | 2 | ... | 4 | ... | ... | 7 | ... |
| 15 | − | + | + | | ... | 2 | 3 | ... | 5 | ... | ... | ... |
| 16 | − | + | | + | ... | 2 | ... | 4 | 5 | ... | ... | ... |
| 17 | − | | + | + | ... | ... | 3 | 4 | 5 | ... | ... | ... |
| 18 | | − | + | + | ... | ... | 3 | 4 | ... | 6 | ... | ... |
| 19 | + | + | − | − | 1 | 2 | ... | ... | ... | ... | 7 | 8 |
| 20 | + | − | + | − | 1 | ... | 3 | ... | ... | 6 | ... | 8 |
| 21 | + | − | − | + | 1 | ... | ... | 4 | ... | 6 | 7 | ... |
| 22 | + | + | + | − | 1 | 2 | 3 | ... | ... | ... | ... | 8 |
| 23 | + | + | − | + | 1 | 2 | ... | 4 | ... | ... | 7 | ... |
| 24 | + | − | + | + | 1 | ... | 3 | 4 | ... | 6 | ... | ... |
| 25 | − | + | + | + | ... | 2 | 3 | 4 | 5 | ... | ... | ... |
| 26 | − | + | | | ... | 2 | ... | ... | 5 | ... | ... | ... |
| 27 | − | | + | | ... | ... | 3 | ... | 5 | ... | ... | ... |
| 28 | − | | | + | ... | ... | ... | 4 | 5 | ... | ... | ... |
| 29 | | − | + | | ... | ... | 3 | ... | ... | 6 | ... | ... |
| 30 | | − | | + | ... | ... | ... | 4 | ... | 6 | ... | ... |
| 31 | | | − | + | ... | ... | ... | 4 | ... | ... | 7 | ... |
| 32 | − | − | + | | ... | ... | 3 | ... | 5 | 6 | ... | ... |
| 33 | − | − | | + | ... | ... | ... | 4 | 5 | 6 | ... | ... |
| 34 | − | | − | + | ... | ... | ... | 4 | 5 | ... | 7 | ... |
| 35 | | − | − | + | ... | ... | ... | 4 | ... | 6 | 7 | ... |
| 36 | − | + | − | | ... | 2 | ... | ... | 5 | ... | 7 | ... |
| 37 | − | + | | − | ... | 2 | ... | ... | 5 | ... | ... | 8 |
| 38 | − | | + | − | ... | ... | 3 | ... | 5 | ... | ... | 8 |
| 39 | | − | + | − | ... | ... | 3 | ... | ... | 6 | ... | 8 |
| 40 | + | − | − | | 1 | ... | ... | ... | ... | 6 | 7 | ... |
| 41 | + | − | | − | 1 | ... | ... | ... | ... | 6 | ... | 8 |
| 42 | + | | − | − | 1 | ... | ... | ... | ... | ... | 7 | 8 |
| 43 | | + | − | − | ... | 2 | ... | ... | ... | ... | 7 | 8 |
| 44 | − | − | + | + | ... | ... | 3 | 4 | 5 | 6 | ... | ... |
| 45 | − | + | − | + | ... | 2 | ... | 4 | 5 | ... | 7 | ... |
| 46 | − | + | + | − | ... | 2 | 3 | ... | 5 | ... | ... | 8 |
| 47 | − | − | − | + | ... | ... | ... | 4 | 5 | 6 | 7 | ... |
| 48 | − | − | + | − | ... | ... | 3 | ... | 5 | 6 | ... | 8 |
| 49 | − | + | − | − | ... | 2 | ... | ... | 5 | ... | 7 | 8 |
| 50 | + | − | − | − | 1 | ... | ... | ... | ... | 6 | 7 | 8 |

Relays 1, 2, 3, and 4 operate when *positive* polarity is applied to lines 1, 2, 3, and 4, respectively; relays 5, 6, 7, and 8 operate when *negative* polarity applied to lines 1, 2, 3, and 4, respectively.

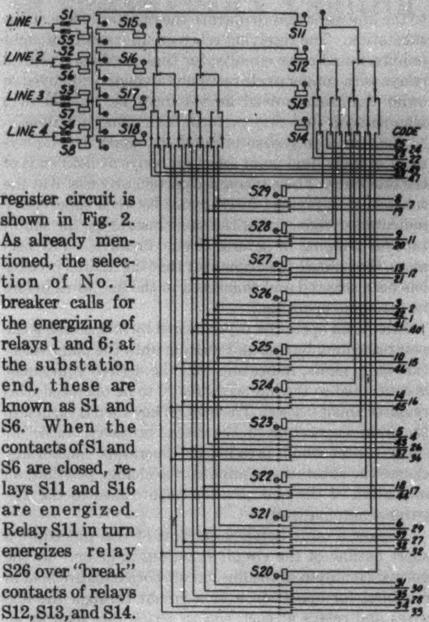

FIG. 2—REGISTER CIRCUIT OF FOUR-WIRE SYSTEM

The two-wire direct selection system utilizes pulsating battery voltage in addition to the direct voltage as utilized in the four-wire arrangement. If direct voltage alone were used, only two selections would be possible over two wires; the addition of the pulsating voltage provides for three more selections or a total of five. Thus on two wires the instantaneous selection of any one of five points is possible.

Referring to Fig. 3, the vibrating relay for producing the pulsating direct current is shown as relay *V*. Just to the right is the push-button arrangement for applying the five different potential combinations to the line wires. On the extreme right are the receiving relays in the substation. The contacts of the receiving relays determine which register relay responds.

The fundamental action in the two-wire polarized selection is as follows: Suppose both contacts of push-

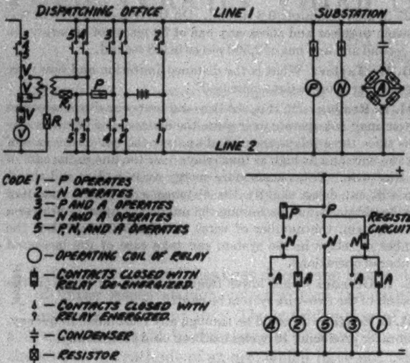

Fig. 3—Schematic Diagram of Two-Wire System

button 1 are closed. Positive battery is applied to the upper line wire and negative to the lower; relay $P$ is energized. Relay $N$ is not affected because of the rectifier valve in series with its operating coil; relay $A$ is not affected because of the condenser. However, if the two contacts of pushbutton 2 are closed, the polarities of the line wires are reversed and relay $N$ responds while relays $P$ and $A$ are unaffected.

Thus, when pushbutton 1 is closed, the circuit may be traced from positive battery, through "make" contacts of relay $P$, "break" contacts of relay $N$, "break" contacts of relay $A$, and the operating coil of relay 1 to battery negative. Thus relay 1 is energized almost instantly after pushbutton is operated. A similar circuit may be traced to energize relay 2 when pushbutton 2 is operated.

When any one of pushbuttons 3, 4, or 5 is pressed, the vibrating pole changer is started, producing pulsating voltage on the secondary of the transformer. This circuit may be traced from positive battery through the contacts of pushbuttons 3, 4, or 5, through two parallel paths to battery negative. The first of these paths goes through the "break" contacts of the vibrator $V$, through the operating coil of $V$ to battery negative; the second path goes through another pair of "break" contacts of vibrator $V$, through half of the primary winding (in the up direction) of the transformer through resistor $R$ to battery negative. Through the first path coil $V$ is energized; this changes the position of its three sets of contacts so that a circuit is completed from battery positive through pushbuttons 3, 4, or 5, through "make" contacts on $V$, and through the other half of the transformer primary winding (in the down direction) and resistor $R$ to battery negative.

As the coil $V$ is energized, it is apparent that the break contact $V$ in series with the operating coil is opened, which, in turn, deenergizes it. Thus the coil is alternately energized and deenergized rapidly. When deenergized, a half wave is produced in the transformer secondary in one direction and the energized position of $V$ produces the other half wave in the opposite direction. The relay now in use produces about 70 cycles per second. The three combinations obtained from this source are full wave pulsating currents, positive pulsating (positive half wave) and negative pulsating (negative half wave), the latter two being obtained by rectifier $P$.

If pushbutton 3 is pressed, the positive half wave is impressed on the line wires. The circuit may be traced from the lower end of the transformer secondary winding, through resistor $R_1$, through rectifier $P$, through pushbutton contact 3, over line wire 1, through the relay circuits of $P$ and $A$ in parallel, over line wire 2, through another contact of pushbutton 3, to the other end of the secondary winding of the transformer. The substation selection circuit may be traced from battery positive, through "make" contact of relay $P$, through "break" contacts of relay $N$, through "make" contacts of relay $A$, through the operating coil of relay 3 to battery negative. Therefore, when pushbutton 3 is operated in the dispatching office, relay 3 in the substation responds.

The action of pushbutton 4 is similar to that of 3, except that the negative half wave is used. Relays $N$ and $A$ respond, which produces a register circuit such that relay 4 responds instantly. When pushbutton 5 is pressed, both half waves are impressed on the line wires so that the three relays $P$, $N$, and $A$ respond and relay 5 is energized.

Since only five selections are available on two wires without going to other apparatus to obtain various voltage or frequencies, the simple way of expanding control is to send more than one selecting combination. With two combinations, any one of 25 can be selected.

Referring to Fig. 4, the first selecting impulse chooses one of the five paths labeled $A$, $B$, $C$, $D$, and $E$. Thus the circuit is completed from positive battery to one of the five groups. After this selection is checked back to the office, the second selecting impulse completes the circuit to the desired relay by energizing one of the relays in the group. If relay No. 17 is to be selected, the first selection would be the fourth code closing contact $D$ and the second impulse would be the second code closing contacts $b$. One operation only is required by the dispatcher for selecting any one of the 25 relays.

In conclusion, the systems described are designed so that they may accommodate all of the auxiliaries used with other previously used assemblies. These include telemetering, remote synchronizing, and position control. The "anti-pumping" feature also is preserved.

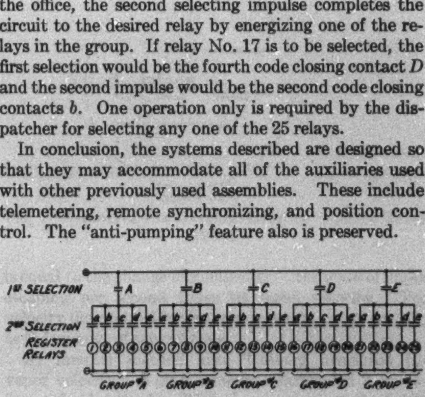

Fig. 4—Schematic Diagram of Two-Wire Receiving Relay Circuits Showing How Two Selections Expand a System from Five Possible Operations to Twenty-five

## Discussion

**S. S. Watkins:** What are the ways and means of eliminating inductive effect in the line wires and also is it possible to spread out the receiving equipment instead of having all of the substation apparatus located in one area?

**M. E. Reagan:** The two-wire system is very easily drained so that inductive interference will not in any way affect operation and the draining of the four-wire system is similar to present four-wire systems in that the receiving relays had to be bypassed by resonant shunt circuits. As far as the spreading out of the receiving equipment is concerned, all of the apparatus to be controlled should be in the same approximate location as the receiving apparatus. Some direct wire stations may be run for considerable distances where they are not subject to inductive interference.

**A. E. Anderson:** Asked about the speed of selection on the new systems.

**M. E. Reagan:** On the two-wire system it is possible to select and check any one of 5 in approximately 0.4 second and any one of 25 in approximately 0.8 second. On the four-wire system it is possible to select and check any one of 50 pieces of apparatus in 0.4 second and any one of 2,500 pieces in 0.8 second.

**D. W. Taylor:** What is the distance limitation and how were the number of operations increased?

**M. E. Reagan:** On this, the two- and four-wire direct selection system may not operate over quite the distances of previous systems since three relays are picked up over the line in the case of the two wire and as high as four relays over the line in the case of the four wire. This means more energy over the line and therefore will cut down slightly the distance over which operation may be obtained. In increasing the number of operations over a given system, the number of wires would not increase but the number of relays in the system can take care of the increased number of operations.

**E. I. Greene:** Could lower frequency than 70 cycles on the pulsator of the two-wire system be used?

**M. E. Reagan:** It could be through any reasonable frequency. A vibrator producing 16 cycles has been used successfully.

# High-Velocity Vapor Stream in the Vacuum Arc

BY R. C. MASON*

Associate, A.I.E.E.

***Synopsis.***—*The discovery and importance of a high-velocity vapor stream issuing from the cathode region of a vacuum arc led to a summary of the experiments showing the existence of a vapor stream and a review of the theories proposed to account for it.*

*The velocities were determined from: (1) force on the cathode and loss weight by the cathode; (2) force on a vane in front of the cathode, and mass of cathode material deposited on the vane; and (3) energy imparted to vane, and mass of material deposited. Methods (1), (2) and (3) on the copper arc gave vapor velocities from 1 to 2.5* $\times 10^6$ *cm/sec, while method (1) on a mercury arc gave an average of 2.24* $\times 10^6$ *cm/sec. Sources of error would not change the above values greatly.*

*Several proposed theories are shown to be inadequate; the one possible theory (Risch and Lüdi) is based upon the presence of multiply-charged ions which leave the cathode after neutralization with a high velocity.*

In the last few years it has been discovered that a blast of vapor issues at high velocity from the cathode region of a vacuum arc. The consideration of this subject is important in the study of the arc. Previous theories of the cathode of an arc, which have not taken account of the vapor stream, must be extended, for the vapor blast, as it now appears, is a part of the cathode phenomena, and as such must be included in any satisfactory theory of the cathode of an arc. The energy carried away in the high-velocity vapor stream, which is not an inconsiderable part of the total energy loss at the cathode, must be included in the heat balance at the cathode. This paper will review the experimental evidence for the existence of the vapor blast, and will discuss the theories proposed to explain its origin.

By "vacuum arc" is meant an arc between metal electrodes in a residual gas at low pressure—a few microns or less. Such an arc burns, near the cathode at least, primarily in the vapor of the cathode material. Vapor of the cathode metal leaves the cathode region with a velocity over $10^6$ cm/sec. Such velocities in themselves are not extraordinary, but in the arc their origin is a matter of wonder. The velocities correspond to equivalent volts† of 36 to over 500—several times the total arc voltage—so that a direct electrical origin is not obvious. Several different methods of observation, described below, yield results of the same magnitude, however.

## Experimental Results

The existence of the high-velocity vapor stream was first discovered by Tanberg[1] who observed and measured a force of considerable magnitude on the cathode of a vacuum arc. A copper rod, suspended freely by a fine wire, as shown in Fig. 1, served as the cathode of the arc. Before the arc was drawn by moving the anode into contact with the cathode, the pressure in the vessel was about 0.2 micron; at the end of a test of a few seconds duration, the pressure had increased to some 10 microns. When the arc was burning the reaction on the cathode caused a deflection of the whole cathode structure; from the length of support and the deflection, the force on the cathode was found. The cathode was weighed before and after a test of known duration so that the loss of weight per second was known. The force is equal to the change of momentum—the mass of vapor escaping per second times its mean velocity. The velocity determined in this way was $1.04 \times 10^6$ cm/sec, as the average of several tests.

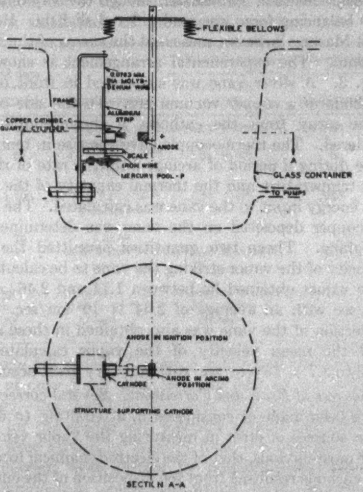

Fig. 1—Apparatus for Determination of Cathode Vapor Speed

By another method also, Tanberg measured the vapor velocity. A glass vane was suspended 2 cm before a fixed cathode. With an arc playing, the vapor issuing from the cathode caused the vane to deflect. From the vane deflection and the mass of copper vapor deposited on the vane per second, the mean velocity of the vapor striking the vane was found to be about $1.35 \times 10^6$ cm/sec.

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†The volt equivalent of the velocity of a particle is the potential through which a singly charged particle of the same mass must fall in order to acquire the same velocity. It is calculated from $eV = \frac{1}{2} mv^2$.

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[1] *Phys. Rev.*, **35**, 1080, 1930.

Kobel[2] observed a large force at the cathode of a mercury arc, and in a similar way calculated a high velocity for the vapor leaving the cathode. The mercury level in a conical tungsten cup was adjusted until the cathode spot just covered the entire mercury surface. The difference in level of the mercury in the cathode cup and in a connecting side tube, shown schematically in Fig. 2, represented the force on the cathode. The loss of mercury from the cathode was measured by observing the rate of change of mercury level in the tungsten cup. From these two quantities the mean velocity of the vapor leaving the cathode region can be calculated. Values from 1.15 to $3.1 \times 10^6$ cm/sec are obtained, with an average of $2.24 \times 10^6$ cm/sec.

All of the results mentioned above were obtained from measurements of momentum, though the way in which the balancing force was read differed slightly. Berkey and Mason,[3] however, measured the *energy* of the vapor stream. The experimental arrangement is shown in Fig. 3. A silver vane was suspended in front of the cathode of a copper vacuum arc. To the side of the vane away from the cathode, a thermocouple was soldered. The thermocouple gave the rise in temperature during a period of arcing; from the rate of rise of the temperature and the thermal capacity of the vane the energy input to the vane was calculated. The mass of copper deposited on the vane was determined by weighing. These two quantities permitted the rms velocity of the vapor striking the vane to be calculated. The values obtained lie between 1.74 and $2.46 \times 10^6$ cm/sec with an average of $2.04 \times 10^6$ cm/sec. The deflection of the vane was also obtained in these tests, and the mean velocity of the vapor calculated as 1.62 to $3.7 \times 10^6$ cm/sec, with not very great accuracy.

*Sources of Error and Corrections.* Several corrections have been made or considered in attempting to eliminate sources of error in measuring the vapor velocity. The most obvious, that of the electrodynamical force on the cathode resulting from the disposition of the current leads was estimated by Tanberg and deducted before the values of velocity given above were calculated. A further electrodynamic force, resulting from the convergence of current flow at the cathode spot, was estimated by Risch[4] to be not over 5 per cent of the measured force. The radiation pressure on the cathode was an entirely negligible factor. The reaction pressure of the electrons leaving the cathode was not over 5 per cent of the total force, as pointed out by Risch.[4] Thus, of the forces upon the cathode measured by Tanberg and Kobel not over about 10 per cent can be attributed to causes other than the reaction of the vapor leaving the cathode region.

None of the above mentioned corrections are applicable to the force on the vane suspended in front of the arc. The mean velocity calculated for the vapor striking the vane can be in error only if the mass involved is incorrect—that is, if some of the vapor striking the vane is reflected without condensation. This seems hardly probable as metal vapors usually condense with little reflection. Furthermore, the amount of copper deposited on the vane was just the amount to be expected if a cosine distribution of the measured loss of material from the cathode existed; and the density of vapor deposited on the walls of the containing vessel followed a cosine law. No great amount of reflection thus seems reasonable. If such did occur, the rms velocity would be more nearly correct than the mean velocity; actually about the same values are secured for each.

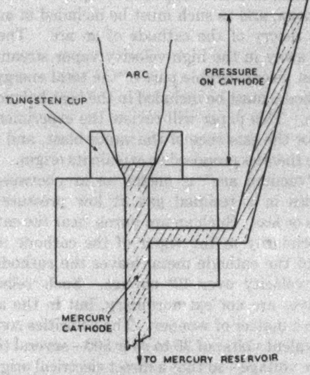

Fig. 2—Kobel's Experiment

The vane may receive energy from the arc, in addition to the energy of the impinging vapor, by radiation and by recombination of ions upon the vane. The radiation energy received was measured experimentally, found to be small, and was subtracted from the total before the rms velocity quoted was calculated. An upper limit to the latter energy would be obtained by considering all the vapor condensing as ionized. Then the energy of recombination would amount to less than 10 per cent of the total.

Other sources of error lie only in inherent difficulties in reading the experimental quantities. While the masses involved could be determined exactly, deflection methods probably permitted no great accuracy in determination of the forces; and Kobel records difficulty in adjusting the mercury levels. It is probable that the energy measurements yield more accurate values of the velocity of the vapor stream than the other methods.

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[2] *Phys. Rev.* 35, 1636, 1930.

[3] *Phys. Rev.* 38, 943, 1931.

[4] *Helv. Phys. Acta.* 4, 122, 1931.

Some of the quantities observed by the different investigators are given in the table. The volt equivalent of the velocity is given in order to aid in explaining the theories offered. For the energy measurements this quantity may be calculated directly; but the mean velocities should be translated into rms velocities before calculating the volt equivalents. A knowledge of the velocity distribution would be necessary in order to get the ratio of rms to mean velocity; for a uniform velocity distribution the ratio is one, while for any other distribution the ratio is greater than one. Since the actual distribution is entirely unknown, the minimum value is the one used in the following table.

## THEORIES

Several theories have been put forward to account for the origin of the high velocity of the vapor. The temperature of the cathode spot is inadequate to give the emitted vapor the velocities calculated. The temperature of the cathode spot of the copper vacuum arc has been estimated to be under 3,000 deg K,[5] while in the mercury arc the cathode temperature is probably only a few hundred degrees. The vapor velocities, however, are the same magnitude as the average molecular velocity of a gas in thermal equilibrium at several hundred thousand degrees so that a purely thermal origin of the high speeds seems impossible.

*Wellman's Theory.* Wellman[6] suggested that, though the reaction of the copper leaving the cathode at 3,000 deg K was small, the reaction of gas evolved from the cathode during arcing might account for the remainder of the observed force. His calculations were based upon an incorrect value of current, however, so that the actual force of the gas is also a small factor. Furthermore, the mass involved in calculating the high velocities was determined by weighing the cathode before and after arcing so that any net loss of gas was included with loss of copper; only gas evolved during arcing and reabsorbed before the subsequent weighing of the cathode would not be discerned. In the mercury arc it seems unlikely that any gas was evolved from the cathode.

*Compton's Theory.* It has been shown by different methods[7, 8] that positive ions drawn to an electrode by an electric field are neutralized but give up to the electrode only part of the kinetic energy acquired from the field; part of the energy is retained and carried away by the neutral molecule. From the similarity to heat and momentum exchange of a gas with a solid the ions are said to possess an "accommodation coefficient" less than unity. Compton proposed that the existence of an accommodation coefficient, whereby neutralized ions leave the cathode with considerable momentum, could account for the reaction upon the cathode of a vacuum arc.

In effect, by this theory a more dense stream of low-velocity particles is substituted for the less numerous high-velocity particles of Tanberg and Kobel. Since the mass of positive ions striking the cathode per second might be much larger than the mass of the net vaporization from the cathode, the observed reaction could be accounted for if the neutralized ions left the cathode with a small part of the energy acquired from the cathode fall space. Compton calculated that a retention of only 2 per cent to 5 per cent of the incident energy—less than 0.5 equivalent volt—would be necessary for the copper and mercury arcs, if half the current were carried by positive ions; if a smaller part of the current were carried by positive ions, then the accommodation coefficient would have to be still smaller. While small values do exist for light atoms, the accommodation coefficient for heavy ions, such as copper or mercury, has not yet been measured.

Even though the mechanism suggested by Compton may possibly picture correctly the way in which the reaction is imparted to the cathode, it has been pointed out[4, 9] that the necessity of a high-velocity vapor stream leaving the cathode region remains. The force on the

| | | | Range of data | | | Results—average of several tests | |
|---|---|---|---|---|---|---|---|
| Observer | Arc | Method | Current amperes | Force dynes | Mass involved | Mean veloc cm/sec | Equiv. volts |
| Tanberg | Copper | Force on cathode | 11 to 32 | 189 to 435 | Avg $1.5 \times 10^{-5}$ gr/amp-sec | $1.04 \times 10^{6}$ | 36 |
| | | Force on vane | 14 to 18 | 63 to 92 | 4.3 to $6.5 \times 10^{-5}$ gr/sec | $1.35 \times 10^{6}$ | 60 |
| Kobel | Mercury | Force on cathode | 30 to 37 | 687 to 1,700 | Avg $1.7 \times 10^{-5}$ gr/amp-sec | $2.24 \times 10^{6}$ | 520 |
| Berkey and Mason | Copper | Force on vane | 20 | 36 to 70 | 2.22 to $2.38 \times 10^{-5}$ gr/sec | $2.48 \times 10^{6}$ | 202 |
| | | Energy imparted to vane | 20 | Energy 3.59 to $7.26 \times 10^{7}$ ergs/sec | 2.22 to $2.38 \times 10^{-5}$ gr/sec | rms veloc $2.04 \times 10^{6}$ cm/sec | 137 |

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5. *Phys. Rev.* **38**, 296, 1931.
6. *Phys. Rev.* **38**, 1077, 1931.
7. *Phys. Rev.* **37**, 1596, 1931.
8. *Phys. Rev.* **37**, 842, 1931.
9. *Phys. Rev.* **37**, 779, 1931.

cathode must be balanced by the momentum of the particles escaping from the cathode region; since a low pressure existed during the experiments, the flow of momentum can be carried only by the vapor corresponding to the net loss in weight of the cathode. Consequently, the velocity calculated for this vapor must be correct. The suggestion offered would not account for the high-speed vapor striking the vane before the cathode. If the Compton theory is valid, then an equal difficulty remains in devising a way by which the many molecules with low velocity may transfer their momentum to a few molecules with high velocity.

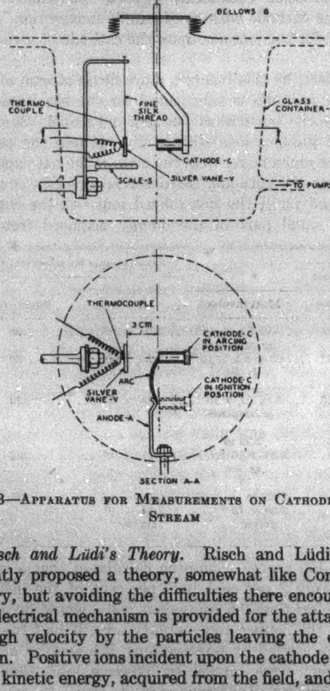

FIG. 3—APPARATUS FOR MEASUREMENTS ON CATHODE VAPOR STREAM

*Risch and Lüdi's Theory.* Risch and Lüdi[10] have recently proposed a theory, somewhat like Compton's theory, but avoiding the difficulties there encountered. An electrical mechanism is provided for the attainment of high velocity by the particles leaving the cathode region. Positive ions incident upon the cathode possess both kinetic energy, acquired from the field, and potential energy, in virtue of their ionization. Risch and Lüdi propose an accommodation coefficient for the potential energy; that is, positive ions are neutralized at the cathode but some of the energy set free in this act is presumed to be converted into kinetic energy of the neutral particle. Most of the atoms evaporated from the cathode are ionized and drawn back before escaping completely; after neutralization, they leave at a high velocity. Upon this assumption, the ion current is equal to the net material loss from the cathode. In order to supply thermal losses from the cathode and to provide for the large kinetic energy of the escaping vapor, it is necessary to suppose that the positive ions are multiply charged—that they have been ionized six or seven times. This Risch and Lüdi believe possible, because such a dense stream of electrons is coming from the cathode that a copper atom would be struck many times while it remained in the cathode region, and the time intervals between collisions would be too short for the atom to radiate away the energy received from the electrons. Thus ionization would proceed by cumulative action until an ion would possess several hundred volts potential energy. Risch and Lüdi's calculations for the copper arc run briefly thus: If 86 per cent of the current is carried by electrons (see below) a current density of 14,000 amp/cm$^2$ corresponds to $7.5 \times 10^{22}$ electrons/cm$^2$-sec. If the cross-section of a copper atom is $10^{-15}$ cm$^2$, each atom will be struck $7.5 \times 10^7$ times per sec, and the mean time between two impacts is about $10^{-8}$ sec—too brief for radiation to occur. The energy lost from the cathode by conduction is taken as 3 watts/amp, and by electron cooling as 7 watts/amp. The loss of $1.5 \times 10^{-5}$ gr/amp-sec of copper is equal to $1.4 \times 10^{17}$ molecules/amp-sec, so if this is taken equal to the ion current,

$$\frac{1}{1.4 \times 10^{17} \times 1.59 \times 10^{-19}} = 44$$

elementary charges must be conveyed per ion. If the ions bear six charges, then 38 electrons (or 86 per cent of the current) must be freed for each positive ion. If the energy of the departing neutralized ion is 140 equivalent volts, then the total energy loss per ion is $(7 \times 38) + (3 \times 44) + 140 = 540$ volts. Of this, kinetic energy can provide $6 \times 15 = 90$ volts (six-fold charge times assumed 15 volts cathode fall), leaving 450 volts to be supplied as potential energy—corresponding to 6 or 7 times ionized. Since an electron would have only 15 volts energy at the cathode fall boundary, at least 30 electron impacts per ion formed is necessary. This would involve only $30 \times 10^{-8}$ sec, too short a time for the ion to move far.

The cross-section for excitation of an atom is considerably less than the kinetic theory cross-section used above, so the time between exciting collisions might possibly be longer than the mean time of existence of an excited atom without radiation. Though this and other minor objections might be raised, at present there seems to be no definite proof of the impossibility of the explanation of Risch and Lüdi. Indeed, in the arc where the energy density is so much greater than in other forms of discharges, it would not be surprising to find higher states of ionization than exist in other discharges. The idea of multiple ions is entirely new to the theory of the arc cathode, and certainly must be taken into consideration as a possibility in the formulation of a theory of the cathode. Any complete theory of the arc must embody an explanation of the origin of the high velocity vapor stream.

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[10] *Zeits. f. Phys.* **75**, (No. 11/12) 812, 1932.

## Discussion

**Elmer C. Easton and Frank B. Lucas:** Mr. Mason's paper has discussed the high velocity vapor stream emitted from the cathode of a vacuum arc. It makes no mention of a similar vapor stream leaving the anode.

At Lehigh University we have conducted experiments to determine the force acting on the electrode of an iron arc in vacuum. Our apparatus consists of two fixed electrodes and one moving electrode mounted in a tank from which the air can be exhausted. The moving element consists of a cylindrical aluminum disk floating in a cup of mercury and fitted with a brass rod which extends radially from the float and which terminates in a clamp through which is passed an iron electrode at right angles to the brass radius rod. The float is counterbalanced so that the electrode is free to revolve in the mercury pool. By passing current through the mercury, an arc can be struck between one fixed electrode and the moving electrode. The arc force causes the moving element to rotate. By applying the current for a short measured interval the moving element can be given an impulse whose value is indicated by the amount of rotation of the moving element. The instrument has been calibrated by means of a pendulum.

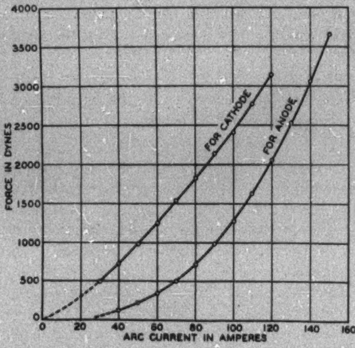

Fig. 1

The force observed was found to differ with the polarity of the moving element. The curves in Fig. 1 show the relation between arc forces and current for each polarity. These observations were part of a preliminary study and were made at a pressure of about five millimeters of mercury. It will be noticed that the force on the anode is very small for current values below 40 amperes.

In order to determine whether or not a high velocity vapor stream was emitted from iron electrodes, a light vane was attached to the end of the moving electrode and the arc struck between the two fixed electrodes. By the same procedure as used by Tanberg and mentioned in Mr. Mason's paper, we calculated the velocity of the vapor streams which were found to come from *both* anode and cathode. Using short current shots of approximately 300 amperes in a pressure of 5 mm Hg, the velocity of the anode stream was found to be about 16 x $10^4$ cm per sec while that of the cathode stream was 23 x $10^4$ cm per sec. It is thought that these velocities would have been higher had the pressure in the tank been less. In the work that will be done when the difficulties encountered in these preliminary tests are overcome, the forces and velocities will be measured in a much better vacuum. The following table shows some of the preliminary test data.

| Arc | Method | Current amperes | Force dynes | Mass gm/sec | Electrode | Rms velocity cm/sec | Pressure mm Hg |
|---|---|---|---|---|---|---|---|
| Iron | Force on vane | 300 | 2,513 | 0.0153 | Cathode | 22.8x$10^4$ | 5 |
| Iron | Force on vane | 302 | 1,435 | 0.0126 | Anode | 15.8x$10^4$ | 5 |

The results of our work so far lead us to suggest that the current values used by Mr. Mason and others working with the arc be increased. Apparently the anode forces are almost unobservable at the low current values (30 amperes) used by Tanberg, Mason and Berkey, and Kobel.

**F. Creedy:** What are the author's precise reasons for supposing that these jets consist of vapor? More than 30 years ago Bredig showed that colloidal particles were emitted by a metal arc operating in a fluid and that these would form an emulsion with the fluid. Is it not at least possible that it is these colloidal particles that we are observing? The surprisingly great magnitudes of these forces and the large amount of material deposited when we use large currents make it difficult to believe that this passes in the form of vapor. I have no suggestions to make as to the mechanism which causes these particles to be projected.

**R. C. Mason:** Previous experiments on the vapor stream from the cathode of the vacuum arc have not been arranged, so far as the writer is aware, in such a way as to test the presence of a similar stream from the anode. At pressures of a few microns, the current and energy densities at the anode are quite small compared to those at the cathode, so it would be surprising to find an anode vapor stream of velocity equal to the cathode stream.

Of course, at low pressures, the cathode vapor jet would impinge on an oppositely placed anode and impart a momentum to it, even if the anode were not emitting a high velocity stream of vapor. In a high vacuum, if the distance between electrodes were small compared to their dimensions, the force on the anode would be just equal and opposite to the force on the cathode. With gas present, the force on the anode would be expected to be less than that on the cathode, and the difference should be greater the higher the pressure and the greater the distance between electrodes, because of the scattering of the cathode vapor stream.

Without the details of the experiment of Messrs. Easton and Lucas using a vane, I am unable to offer any suggestions as to the origin of the apparent anode vapor stream. If an anode stream of velocity almost equal to the cathode vapor jet should be found real, an explanation of its mechanism would seem even more difficult to devise than does an explanation for the cathode stream.

No microscopic examination of the material deposited from the cathode has been made, but it seems reasonable to me that in the cathode region at least the material exists in vapor form. Conditions in the vacuum arc differ so greatly from conditions in an arc in a liquid, it seems improbable that colloidal particles such as exist in the latter are ejected from the former. Whatever the size or mass of the particles of cathode material, however, the velocity calculated would be the same.

# New Studies of the Arc Discharge

BY J. LELAND MYER*

***Synopsis.****—The equation $V = A + B/I^n$ which correctly represents all normal arc characteristics is used as the starting point for a general discussion of arc phenomena and industrial applications.*

*Tests of this equation are applied to iron arcs in various gas atmospheres to obtain a series of values for A and B, making possible certain deductions about arc voltage variations and significance of the characteristics.*

*In limiting the current exponent n, the anode temperature must exert considerable influence on the discharge as a whole. Suggestions are given why this may be so. A value of n is predicted from the arc stream geometry, and is compared with actual values of n for various arcs.*

*From energy considerations of this equation new concepts of the "minimum energy" and the "excess energy" requirements in the arc conduction process are gained. Some applications to arc problems prove these concepts valuable. On this basis high temperature arcs are shown to be the most efficient.*

*Light intensity and probe measurements on the arc stream suggest a new physical picture of high current arcs. Some difficulties are removed in accounting for energy equilibrium at the welding arc cathode.*

FOR nearly a century the phenomena of the electric arc have been studied from the viewpoints of classical physics and commercial application. Keen interest has recently given a strong impetus to investigations in both fields, so that the already copious literature of the past has been greatly enlarged. Unfortunately from all this work there has been little crystallization of opinion about certain phases of the fundamental arc theory. Many details of the exact discharge mechanism have evaded discovery for a long time, so that our basic concepts are not yet complete.

For physicists the electric arc presents an important field for studying the atom and electron. In the laboratory therefore attention has been confined to arcs on a small scale, usually under the simplest and most desirable conditions for experiment. The interesting phenomena at the cathode are now well understood, and many pertinent features of the discharge have been rather fully investigated. Probably the best survey of this subject has been given in an excellent paper by Professor K. T. Compton.[1]

Arcs used in engineering practise and industrial applications are much more complicated than those studied by the physicists. While simplicity and understanding of the phenomena are not the prime considerations in experimenting with such arcs, it is surprisingly true that commercial practise is often far in advance of theory. There can be little doubt however that more rapid progress might result under the guidance of theory and basic experiments properly executed. The present paper deals with some considerations which may bring theory and practise into somewhat closed agreement.

## The Correct Arc Equation

There is hardly another item connected with arc research that has received as much attention, both in point of time and number of investigators, as the characteristic equation of voltage, current and arc length. It may well serve as a starting point for a more general discussion of the discharge.

Ayrton[2] was able to write a successful equation of the form

$$V = A + B/I \tag{1}$$

for the static characteristic of the carbon arc. For energy considerations (1) becomes

$$VI = AI + B \tag{2}$$

expressing the total energy input as some constant plus a linear function of the current for carbon arcs of given length. When applied to the characteristics of metal arcs (1) was a close approximation if the constants $A$ and $B$ were properly adjusted. But the equation was valid only over limited portions of the characteristics, and could not be made to represent them entirely.

In their investigations on metal arcs Malcolm and Simon[3] pointed out that the total energy *vs.* current relations were not straight lines, as equation (2) would indicate, but they were curves slightly concave to the current axis. Steinmetz[4] was able to prove that the characteristics were definitely hyperbolic, but in place of (1) could be better represented by a general equation

$$V = A + B/\sqrt{I} \tag{3}$$

Such equations likewise were limited in their application, and were not truly general for all arcs.

It remained for Nottingham[5] through a systematic study of numerous arc characteristics to establish a correct general equation of the form

$$V = A + B/I^n \tag{4}$$

which, it will be noted, differs only in the current exponent $n$ as compared to (1) and (3). This current exponent is a variable and, curiously enough, has been found to *vary directly with the boiling or sublimation temperature of the anode material* by the relation

$$n = 2.62\,(10)^{-4}\,T \tag{5}$$

The fact that carbon boils at 3,770 deg $K$ (Van der Waals) gives the exponent $n$ a corresponding value of 0.987, making equations (1) and (4) almost identical

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*Engineering Foundation Research Fellow on research being conducted by the laboratories of Lehigh University under the direction of Dr. Gilbert E. Doan.

1. For numbered references see bibliography.

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for carbon arcs, and explaining the early success of the former.

The validity of equation (4) can best be tested by making a logarithmic plot of $(V - A)$ *vs.* $I$. If the data support this test, the points will lie on straight lines of negative slope $n$. Such tests are most easily carried out on those portions of the arc characteristics between one and ten amperes current and one to ten mm arc length. For currents below one ampere the voltage is usually unstable. Above ten amperes the electrodes melt rather rapidly, and also the term $(V - A)$ becomes vanishingly small as the voltage begins to approach its limiting value

$$V = A \tag{6}$$

a relation known to exist in heavy current arcs. Arc lengths less than one mm and greater than ten mm introduce further difficulties in obtaining accurate values of voltage and current. Nottingham has successfully applied equation (4) to many normal arcs over this range of the characteristics. In addition to the original work there is further verification by Anderson and Kretchmar[6] and by Doan and Myer.[7] The positive results of these numerous tests establish (4) as a true general equation for normal arcs, and its correctness has never been questioned.

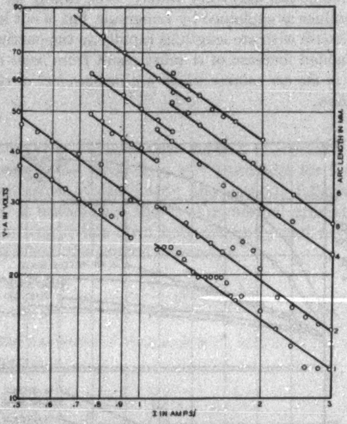

Fig. 1—Test of Equation for the Iron Arc in Air (Cady and Arnold Data)

**IRON ARC IN AIR**
First Stage

| *L* | *A* | *B* | *n* |
|---|---|---|---|
| 1 | 29.1 | 23.5 | 0.71 |
| 2 | 37.5 | 30.4 | 0.71 |
| 4 | 43.0 | 40.6 | 0.73 |
| 6 | 46.0 | 50.7 | 0.74 |
| 8 | 47.3 | 64.0 | 0.73 |

**IRON ARC IN AIR**
Second Stage

| *L* | *A* | *B* | *n* |
|---|---|---|---|
| 1 | 19.1 | 27.7 | 0.69 |
| 2 | 21.5 | 35.6 | 0.69 |
| 4 | 24.0 | 50.2 | 0.71 |
| 6 | 25.1 | 60.8 | 0.73 |
| 8 | 26.6 | 72.5 | 0.72 |

Unfortunately nothing further has resulted from the discovery and verification of this equation. Physicists have long considered emission at the cathode as the essential and controlling feature of the discharge, since all other phenomena appear to be either consequences of this emission or prerequisites to it. The influence of the anode temperature was completely unsuspected and, so far as the writer is aware, has never been explained. However, there is reason to believe that the marked success of this equation may well indicate an important and predominating role of the anode temperature which may give new clues about the discharge mechanism. Before discussing this point directly it may be well to examine some tests of the equation (4) in the hope of enlarging our ideas about its functioning and possibly its interpretation. To gain a complete understanding would require an examination of numerous arcs under systematically varied conditions. For the present study the existing data on short, low current arcs between iron electrodes in various gas atmospheres must suffice.

## Equation Applied to Iron Arcs

The arc between iron electrodes in air is known to make a transition from a first (high voltage) stage to a second (normal voltage) stage at about one ampere. This transition was investigated by Cady and Arnold[8] whose experiments show the excess voltage of the first stage to lie in the anode fall. This is attributed to a temperature equilibrium at the anode which is below the limiting value of the boiling point. It will be interesting to apply the test of equation (4) to both stages, and note whether the value of $n$ gives any indication of such temperature conditions at the anode.

Fig. 1 is a test of the original data, and demonstrates that the equation applies not only to the second (normal voltage) stage as was previously known, but also to the first (high voltage) stage. The constants $A$ and $B$ are different for the two stages, as must be expected from the different positions of the characteristics, but the values of $n$ are the same, and therefore imply equal anode temperatures in both stages.

The writer's data for the iron arc over both stages differ slightly from Cady and Arnold's, possibly because the electrodes were smaller and of different quality metal. The data likewise confirm the tests of equation but with different values of $A$ and $B$.

The normal iron arc has been found to operate very steadily at low voltage in atmospheres of the inert gases argon, helium and neon, when slight contaminations of the gas or electrodes are present. (Under conditions of rigid purification, Doan and Myer[9] have found it impossible even to strike an arc in inert gases.) With impurities present in all three gases the test of the equation is supported equally as well as for the iron arc in air. Fig. 2 shows these tests for the arc in helium. In argon and neon the results are very similar, with lower values of $A$ and $B$.

From these tests there now exists a series of determinations for the constants $A$ and $B$ of the iron arc in various gas atmospheres and in different stages of the characteristic. A comparison may give some idea about their significance and interpretation.

### THE SIGNIFICANCE OF *A* AND *B*

In Fig. 3 are given the variations of *A* and *B* with the arc length. For these short arcs the values of *A* may be extrapolated toward zero arc length, if this be regarded only as an elimination of the effects of the discharge stream. (There is evidence that the anode and cathode falls cancel off as the electrodes actually approach zero arc length.) So extrapolated, the curves for *A* are seen to converge toward a common point $A_o$ = 15 volts. Therefore it is likely that $A_o$ *is basically characteristic of the electrode material.* If the effects of the arc stream have been eliminated, $A_o$ might then represent the combined anode and cathode falls, or at least that portion of them which is independent of current.

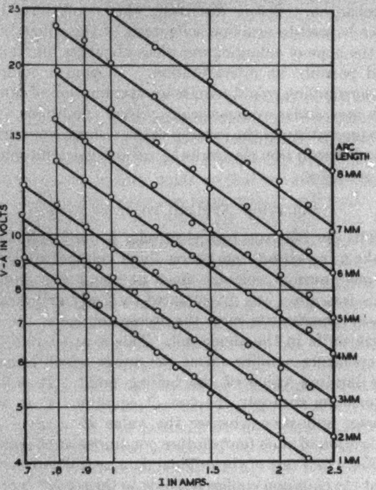

FIG. 2—TEST OF EQUATION FOR THE IRON ARC IN HELIUM

IRON ARC IN HELIUM

| *L* | *A* | *B* | *n* |
|---|---|---|---|
| 1 | 16.6 | 7.1 | 0.701 |
| 2 | 17.8 | 8.3 | 0.705 |
| 3 | 18.4 | 9.5 | 0.709 |
| 4 | 19.7 | 11.4 | 0.717 |
| 5 | 20.4 | 13.7 | 0.714 |
| 6 | 21.4 | 16.4 | 0.720 |
| 7 | 21.9 | 20.0 | 0.722 |
| 8 | 22.6 | 24.7 | 0.728 |

The lack of extensive data makes it impossible accurately to check the value of $A_o$ on this assumption. Child[10] has measured the cathode fall of an iron arc as 13.9 volts and Grotrian[11] as 15 volts. Both values were obtained with the uncorrected probe method, and may not be correct. For the mercury, cadmium and thallium arcs the cathode falls have been more accurately determined, and are about equal to the ionization potential of the metals. This analogy might be carried to the iron arc, except that the ionization potential for iron is variously given as 5.3, 6.5 and 7.8 volts. An approximate check may be made from the known drop of 17 to 19 volts across heavy current iron arcs of very short length. Allowing several volts for the arc stream fall, 15 volts seems to be of the right order for the combined anode and cathode falls at high currents.

To explain the increase of *A* with arc length the anode and cathode falls are not sufficient. The cathode fall is believed to be independent of current, and also of arc length except when the length approaches zero. The anode fall may vary widely, even taking on negative values as explained by Langmuir, but is not known to increase with arc length as rapidly as the curves rise. The added increase of *A* must result from *some conditions in the arc column which are independent of current variation.*

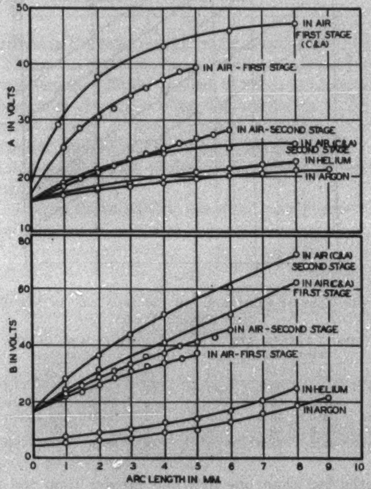

FIG. 3—VARIATIONS OF *A* AND *B* WITH ARC LENGTH

The values of *B* show the variations of this constant to be strongly influenced by the *nature of the gas* in which the arc is operated. Similarly extrapolated, $B_o$ differs for each gas, and may be an index for the initial rate of change of the anode fall (possibly the cathode fall also) occurring in each gas. For air the variation of *B* is nearly linear, and therefore representative of conditions in the arc column which change with length. For the inert gases *B* increases more rapidly than the linear rate with arc length, and may be connected in some manner with the elastic impacts in inert gases which are known to alter conditions in the arc column.

Altogether the variations of $B$ with arc length do not give a very clear picture. It must be remembered that $B$ is primarily an *index of those factors which vary with the arc current*, and its significance becomes plainer when considered in connection with equation (4) where it occurs in the term $B/I^n$. It will later be shown that this term has the nature of an *efficiency factor in the current conduction process* of the discharge.

Experiments reveal that the complete relation between voltage, current and arc length cannot be expressed by an equation less complex than

$$V = \left(\alpha_\infty + \frac{(\alpha_1 - \alpha_\infty)}{I^n}\right)\left(1 - \epsilon^{-dL}\right) + \left(\beta_\infty + \frac{(\beta_1 - \beta_\infty)}{I^n}\right)\left(1 - \epsilon^{-\left(\delta_\infty + \frac{(\delta_1 - \delta_\infty)}{I_n}\right)L}\right) + \left(\gamma_\infty + \frac{(\gamma_1 - \gamma_\infty)}{I^n}\right)L \qquad (7)$$

of which (4) is a special form when $L$ is constant. In equation (7) the term $(1 - \epsilon^{-dL})$ provides for a cancellation effect of the anode and cathode falls when the arc is exceedingly short. For normal arcs above one mm length this term becomes unity and may be removed from the general expression.

$$\left(\gamma_\infty + \frac{(\gamma_1 - \gamma_\infty)}{I^n}\right)L$$

gives the variation of $A$ and $B$ with length of the positive column.

$$\left(\beta_\infty + \frac{(\beta_1 - \beta_\infty)}{I^n}\right)\left(1 - \epsilon^{-\left(\delta_\infty + \frac{(\delta^1 - \delta_\infty)}{I_n}\right)L}\right)$$

is either the total anode fall, or the variation of the anode fall with arc length and the rate of change of that variation with arc current. No systematic tests have ever been made to verify this assumption, but some few calculations have shown that it does not express the anode fall as measured. Therefore the first term

$$\left(\alpha_\infty + \frac{(\alpha_1 - \alpha_\infty)}{I^n}\right)$$

may include some portion of the anode fall in addition to the total cathode fall.

The deductions made from Fig. 3 and equation (7) give some idea of the manner in which $A$ and $B$ operate correctly to represent the arc characteristic. Quantitative measurements in individual portions of the arc discharge are greatly needed to make this interpretation complete and exact. When these become available it should be possible to replace equation (7), which was derived purely from graphical analysis of the characteristic curves, by an equivalent expression which clearly represents the exact conditions and variations throughout the arc discharge.

## SIGNIFICANCE OF THE EXPONENT $n$

While $A$ and $B$ have been found to vary in a not too simple manner, the exponent $n$ should be a constant according to the equation

$$n = 2.62\ (10)^{-4}\ T \qquad (5)$$

If $n$ really depends upon a temperature effect extending from the boiling anode into the positive column, a variation might be anticipated with increasing arc lengths. Optical pyrometer measurements on ten-ampere carbon arcs[12] register temperature variations of over 2,000 deg $C$ in the positive column, although there is an indication of constant temperature over considerable portions of the discharge.

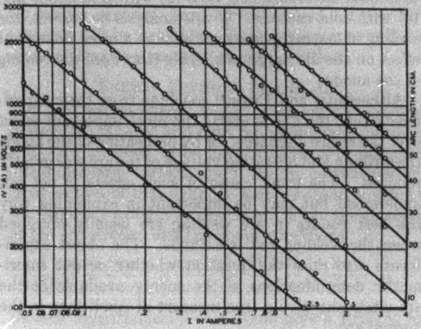

FIG. 4—TEST OF EQUATION FOR THE IRON ARC IN AIR

| $L$ (cm) | $A$ | $B$ | $n$ |
|---|---|---|---|
| 2.5 | 50 | 117 | 0.77 |
| 5.0 | 70 | 190 | 0.81 |
| 10.0 | 110 | 345 | 0.85 |
| 20.0 | 180 | 720 | 0.88 |
| 30.0 | 260 | 1,050 | 0.89 |
| 40.0 | 350 | 1,440 | 0.90 |
| 50.0 | 400 | 1,910 | 0.91 |

This point can perhaps best be tested by using Grotrian's[11] data on low current, high voltage, iron arcs of great length in air. Such arcs might still be considered as normal arcs, except for the fact that the anode was water-cooled to prevent rapid melting. (Nottingham found that when the anode of tungsten arcs was below the boiling temperature, the exponent $n$ was below the normal value.) In Fig. 4 Grotrian's data are shown to support the test of equation, but the values of $n$ are above normal, increasing with the arc lengths.

Normal arcs of shorter length also exhibit systematic variations of $n$ as given in Table I. The general tendency is for $n$ to approach unity, as if this fulfilled some

TABLE I—VARIATION OF *n* WITH ARC LENGTH IN NORMAL ARCS

| Arc length mm | W in air | Cu in air | Fe in argon | Fe in helium |
|---|---|---|---|---|
| 1 | | | 0.700 | 0.701 |
| 2 | 1.49 | | 0.701 | 0.705 |
| 3 | 1.46 | 0.660 | 0.707 | 0.709 |
| 4 | 1.41 | 0.658 | 0.709 | 0.717 |
| 5 | 1.38 | 0.673 | 0.714 | 0.714 |
| 6 | 1.35 | 0.677 | 0.718 | 0.720 |
| 7 | 1.35 | 0.675 | 0.726 | 0.722 |
| 8 | 1.34 | 0.673 | 0.732 | 0.728 |
| 9 | 1.34 | 0.677 | 0.729 | |
| 10 | 1.32 | 0.670 | | |

natural condition of stability for the arc discharge. This occurs also in Fig. 5, in which Nottingham's values for the constants are applied to Malcolm and Simon's[3] data for a copper arc operated (1) normally with both electrodes hot, then (2) with cold anode and (3) with cold cathode. If this analysis be correct, the cooling of the cathode seems to have a more important effect on the discharge as a whole than does the cooling of the anode.

Altherthum and Ewest[13] conclude from their experiments that the anode exerts the more important effect over the entire discharge, for by preheating of the anode the striking and operating voltage of the arc was greatly reduced. The exact cause of such effects is not yet understood but may be important in explaining why the best results in arc welding are usually obtained when the welding rod is cathode. The above experiments also raise the question whether or not calorimetric determinations of the energy available at the arc electrodes give a true measure of conditions in the normal arc.

### INFLUENCE OF THE ANODE TEMPERATURE

Hagenbach and Langbein[14] find that in normal arcs the anode is always boiling. When the atmosphere is non-oxidizing the cathode is heated less than the anode, but when both electrodes oxidize they reach the same temperature. Thus there arises the possibility that the effect of the anode temperature is shared by the cathode temperature which may be equal or nearly so. Experiments with arcs between totally different anode and cathode materials always reveal *n* to be characteristic of the anode boiling or sublimation temperature.

Conditions at the anode give no indications of this far reaching effect of the anode temperature. The anode spot is thought to be surrounded by swarms of ions and electrons moving in a somewhat random motion. If at any moment the excess of electrons over positive ions reaching the anode is greater than the current in the arc circuit, a counteracting field sets in to repel the slower electrons; *vice versa*, and deficiency of electrons results in a strengthening of the field until the proper current is obtained. In this process the anode temperature does not seem to play any part, so that its effect must extend beyond the anode fall.

Beyond this region is the positive column which occupies the major portion of the arc stream length and exerts a considerable influence on the discharge characteristic as a whole. In the column intense ionization is taking place, always sufficient to replenish the large number of ions lost by recombination and diffusion. The ionization may be produced either thermionically or photoelectrically, and may be a combination of these methods. In the carbon arc the ionization is ascribed principally to high temperature,[15] and may therefore be controlled in some manner by the limiting temperature of the anode.

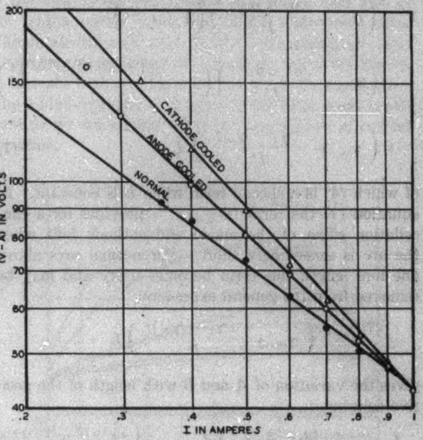

FIG. 5—EFFECT OF COOLING THE ELECTRODES—COPPER ARC IN AIR

| | *A* | *B* | *n* |
|---|---|---|---|
| Normal | 32 | 44 | 0.69 |
| Anode cooled | 40 | 43 | 0.88 |
| Cathode cooled | 50 | 43 | 0.98 |

(Arc length 4 mm)

Nottingham[16] has found that when the arc anode and cathode are more or less equally volatile, the anode material usually becomes the "active" gas in the arc column. The temperature of this active gas could strongly influence its absorbtion properties, and therefore control the relative efficiency of the current conduction processes in this part of the arc. More evidence on this point will appear from energy considerations, which show that for high temperature arcs the conduction efficiency in the arc column is greatly improved.

While the function of the anode boiling point cannot be definitely explained, it can be stated that the important effect is the temperature and not any physical property associated with the boiling or sublimation point of the material. This temperature appears to impose an upper limit upon the activity and possibly the efficiency of certain processes in the arc stream. If in some manner the absorption and ionization properties of the active gas could be shown to be generally characteristic of this limiting temperature, it should prove to be a valuable starting point in explaining this important phenomenon. Any progress in this direction will be difficult, since conditions at the surface of the arc stream prevent direct observations or measurements of the interior.

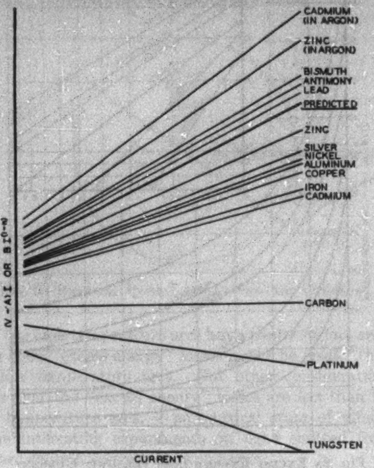

Fig. 6—Total Excess Energy Losses

## Energy Considerations

For very large currents theory and experiment show that the arc characteristic is approaching the form

$$V = A \tag{6}$$

For infinite currents it is clear that the arc mechanism is *conducting the current at a minimum expenditure of energy per unit of current.* This minimum is determined by the lowest possible values of the following:

1. Anode and cathode falls.
2. Losses incident to conduction within the arc stream.
3. Losses external to the arc stream, such as radiated heat and light, and diffusion of ions.

For currents less than infinity items 1 and 3 are known to increase while 2 might increase a slight amount but probably remains almost constant. The total conduction efficiency of the arc therefore falls off as the currents diminish, for the expenditure of energy per unit current has grown larger. In other words, *the decrease in conduction efficiency makes it necessary to add to the right hand side of equation* (6) *the term* $B/I^n$, which becomes

$$V = A + B/I^n \tag{4}$$

an equation known to represent the arc characteristic correctly. As the current enters to the $-n$ power, the losses vary inversely with the current, and this accounts for the *falling* characteristics of the volt-ampere curves and the so-called *negative resistance* of the electric arc.

The energy form of equation (4) may be written as

$$VI = AI + BI^{(1-n)} \tag{8}$$

which involves the total amounts of energy instead of the energy per unit current. For any current, $AI$ is the *minimum conduction energy at "infinite current" conditions.* $BI^{(1-n)}$ or its equivalent $(V - A) I$ might be called the *"excess energy requirement" by virtue of the fact that conduction losses have increased as the currents are farther removed from infinite values.* These new concepts will be valuable. Their importance will become evident in some further considerations.

## Energy Division in the Arc

If the "excess energy losses" were entirely confined to item No. 3 (heat and light radiation, ionic diffusion) and were assumed to be linear functions of the cylindrical discharge surface, and if the arc current per unit cross section of that cylinder were constant, a value of the exponent $n$ might be predicted. From the geometry of the arc stream, and the above conditions

$$\frac{\text{total excess losses}}{\text{total arc current}} \,\alpha\, \frac{\text{arc cyl. surface}}{\text{arc cross section}} \,\alpha\, \frac{2\pi r}{\pi r^2} \,\alpha\, \frac{2}{r}$$

Plotted logarithmically this would give a straight line relation with slope $(1 - n) = 0.5$ or $n = -0.5$. Fig. 6 shows schematically how the actual "excess energy losses" of various arcs compare with this predicted value.

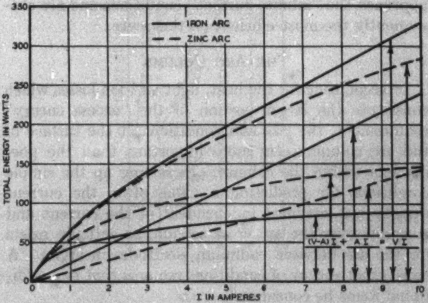

Fig. 7—Division of Energy in the Arc

The curves for lead, antimony and bismuth seem to correspond rather closely with this derived value of $n$. Actually the cadmium arc in argon, with $n = -0.275$, has been found to have a constant current density, at least over the 1—10 ampere region, thus fulfilling the geometrical conditions used in predicting a value of $n$. It is evident that theoretical predictions on such a basis are useful in giving a picture of the arc processes. When the ratio of losses in items 1, 2 and 3 becomes known and the factors regulating current density are evaluated, such predictions will be accurate and valuable.

Returning to the energy equation (8) it is possible to show how the "minimum energy for infinite current conditions" and the "excess energy" combine to represent the total energy input into the arc. In Fig. 7 such a division of energy is shown for zinc and iron arcs of 4 mm length. In comparing the currents at which the energy $BI^{(1-n)}$ is of the same magnitude as the $AI$ energy, this condition occurs at 2.5 amperes for the iron arc and at about 10 amperes for the zinc arc. This analogy may be carried to other arcs to demonstrate that the "excess energy requirement" falls off more rapidly as $n$ becomes larger, *i.e.*, as the anode temperature becomes higher, in the normal arcs.

The same conclusion may be drawn from an examination of the energy expenditures per unit current as implied in equation (4). A plot of $B/I^n$ *vs.* $I$ will have exactly the shape of the voltampere characteristics displaced a distance $A$ above the current axis. (Incidentally, all our tests of log $(V - A)$ *vs.* log $I$ as in Figs. 1, 2, 4 and 5 deal only with this "excess energy" and the exponential rate at which it varies with current.) In Figs. 8A and 8B such relations are given, both in logarithmic and rectangular coordinate plots, for a large number of arcs of 4 mm length. The rapidity with which the curves approach zero is seen to depend upon $n$, and therefore upon the anode temperature, indicating that high temperature arcs more rapidly approach the "infinite current" conditions and are consequently the most efficient on this score.

## THE ARC COLUMN

In accounting for the heat, light and ion losses which constitute the larger portion of the "excess energy" requirement, the size and conditions at the surface of the arc column seem more important than the phenomena within the column. In setting up the simple conditions for predicting a value of $n$, the current density was assumed independent of the current and constant over the arc cross section, as actually exists for the arc between cadmium electrodes in argon. A more exact survey of conditions requires that two additional items be considered.

1. The cumulative magnetic field of the conducted current is tending to concentrate the discharge about a longitudinal axis in its center. This is called the "pinch effect." It was fully described by Northrup[17] and was used by Barlow[18] in explaining why the arc did not spread out as the glow and other types of discharges do. The physical picture is given in Fig. 9 where the magnetic intensity curve is superimposed upon a cross section of the discharge column. The cumulative magnetic field $\beta$ creates a barrier just at the edge of the arc stream, and exerts its greatest inward pressure on the ions at this point.

2. The high temperature inside the arc discharge exerts a diffusion pressure opposing the concentrating effect of the magnetic field. Equilibrium between these opposing forces establishes the position of the magnetic barrier and surface of the discharge stream in relation to the central current axis.

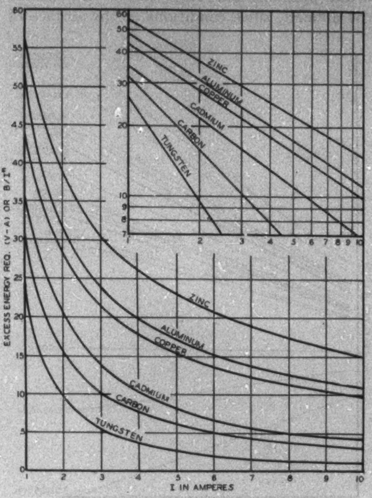

FIG. 8A EXCESS ENERGY LOSS PER UNIT CURRENT

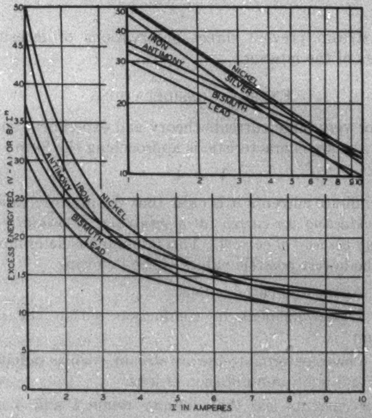

FIG. 8B—EXCESS ENERGY LOSS PER UNIT CURRENT

The logical deduction is that for high temperature arcs the positive column is somewhat larger in cross section than for low temperature arcs carrying the same current. Actual observations have shown this to be the case for copper, carbon and tungsten arcs in air. The relative enlargement is not very great, but the current density does decrease with temperature increase, in agreement with the above items.

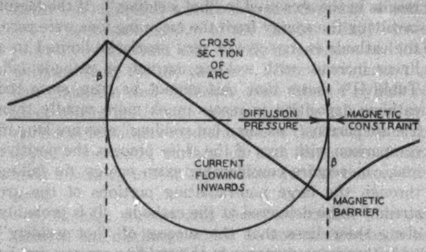

Fig. 9—Physical Conditions at the Arc Surface

If the high temperature arcs have *greater surface area*, then their "excess energy" losses might be *greater* than for low temperature arcs. But other considerations show that the "excess energy" losses are *less* than for low temperature arcs, a paradoxical state of affairs. Some interesting experiments on light emitted from the arc column suggest an explanation.

Nottingham[19] has measured the light per unit volume emitted from the arc. When plotted against current, as given in Fig. 10, the curves are seen to approach a "saturation value" in the order of increasing temperature—cadmium (in argon), copper, carbon and tungsten in air. The efficiency of the high temperatures seems to *limit the depth* from the arc surface through which the light and other radiation escapes, so that in spite of the increased surface areas the high temperature arcs are still more efficient than the low temperature arcs. Saturation of the emitted light per unit volume might then be thought to occur when there is some portion of the discharge which no longer contributes to this emission.

## Arc Extinction

As the term $B/I^n$ is a measure of the *rate of energy removal* from the discharge, it could play an important part in arc extinction. The most difficult arcs to extinguish would be those of high efficiency (low values of $B/I^n$). The increase of $B$ with arc length helps to explain why long arcs are more easily extinguished than short arcs, a basic principle employed in most circuit interrupters. The vanishingly small value of $B/I^n$ for very heavy currents allows an insignificant portion of the energy to be dissipated, and gives some idea of the difficulties in interrupting such circuits.

On the basis of these suggestions the contacting metals should be a matter of some importance in successfully interrupting a circuit. Since arcs between metals of low melting point show the greatest rate of energy dissipation, such metals should help to extinguish the arcs more quickly. Some recent experiments by Browne[20] show that this is not the case. The results of his tests in Fig. 11 prove that the arcs between high melting point metals are most easily extinguished. The fundamental differences between a-c arcs as used by Browne and d-c arcs as previously considered in this discussion removes this apparent contradiction.

While Fig. 9 is probably a correct physical picture of conditions in a d-c arc, it is only momentarily applicable to a-c arcs. In every cycle the magnetic barrier twice drops from a maximum through zero to a maximum in the reverse direction. In these 120 intervals each second when the magnetic and electric fields are removed, the ions can freely diffuse out of the arc stream *at a rate depending upon their temperature.* Of course there are other pertinent features involved in the exact theory of arc extinction, but this discussion helps to remove an apparent contradiction between theory and experiment.

## Arc Welding

Very few physical measurements have ever been made on heavy current arcs of the type used in arc welding, so that most of our concepts have been carried over from the smaller arcs studied in the laboratory. Doan[21] has set up the conditions of energy balance at the cathode of a welding arc, calculating the heat sources as indicated by the contemporary physical theories of the mercury and tungsten arcs. When applied to iron arcs of 150 amperes, theoretical calculations account for only half of the energy disbursed at

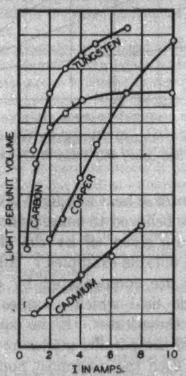

Fig. 10—Light Saturation Curves; Scale Not the Same for all Arcs

the cathode. While the constants of the iron arc have never been accurately determined, corrected values might bring the calculations into somewhat better agreement but would hardly make up the existing deficit.

As Doan has suggested, the greatest source of error probably lies in neglecting the heat of condensation of incoming positive ions. In low current arcs of the mercury and tungsten type this heat source is vanishingly small, but for heavy current arcs it may be considerable if the following reasoning is correct.

The heat, light and ionic diffusion losses from the arc column may be thought to come from a cylindrical layer rather than a surface. This seems consistent with the light per unit volume curves for low current arcs which show saturation as soon as a portion of the discharge along the central axis no longer contributes to the outside losses. In high current arcs this non-radiating, high efficiency portion becomes increasingly greater. (The intense heat and light often accompanying such arcs are believed to come principally from hot or burning vapors given off by the electrodes. The flaming arcs are notable examples.) All these losses in the outer layer are compensated by energy derived from the electric field which assumes a value commensurate with these losses. If the equipotential surfaces of this field are parallel planes at right angles to the arc stream, then the innermost non-radiating portions will derive an excess of energy above that which is needed for the ordinary ionization processes. This extra energy, since it results from a directed field, would seem to have a directed temperature effect enabling the current carriers eventually to contribute this energy as heat to the electrodes. The positive ions of the arc stream might thus reach the cathode in larger numbers than are now suspected, and their heat of condensation would be a large item.

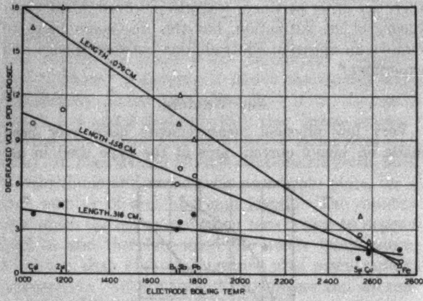

FIG. 11—RATE OF VOLTAGE DECREASE FOR ARC EXTINCTION. FROM BROWNES 300-AMP, 450-VOLT A-C ARC EXPERIMENTS

Such assumptions do not violate our physical picture of small current arcs, and yet provide an additional heat source which is certainly needed to satisfy the energy equilibrium conditions at the cathode of heavy current arcs. Furthermore they are in good agreement with probe measurements which show that as the probe sweeps through the inner portions of the arc stream the *positive ion current per unit length of the probe* increases rapidly with the arc current.

A logical deduction is that these positive ion currents help to explain the very rapid cathode deposition which results in the arcs used in "hot welding." If the factor involving the energy from the incoming ions were zero, the cathode energy would very nearly be limited to a linear increase with welding current or cathode fall. Table II[22] shows that this cannot be true, since the cathode deposition increases much more rapidly than the arc current. As the "hot welding" arcs are long in comparison with arcs of the older process, the positive ions can acquire considerable extra energy (in falling through the large non-radiating portions of the arc stream) to be delivered at the cathode. It is probably along these lines that the success of "hot welding" and other improvements in the welding process can be explained.

TABLE II—TYPICAL CURRENT AND CATHODE DEPOSITION OF "HOT WELDING" ARC

| Arc current amperes | Cathode deposition pounds per hour |
|---|---|
| 300 | 5.0 |
| 350 | 7.5 |
| 400 | 10.0 |
| 500 | 15.0 |
| 550 | 20.0 |
| 600 | 25.0 |
| 700 | 30.0 |
| 750 | 35.0 |

## GENERAL CONCLUSIONS

The following concepts of the arc discharge phenomena are indicated from these new studies:

1. There is a "minimum energy" requirement of $A$ watts per unit current in the arc conduction process, implying (a) a minimum of potential in drawing the charged particles into or out of the electrodes, and (b) the highest efficiency in conveying these charges through the arc stream. These conditions actually exist when the arc current approaches infinite values.

2. There is an "excess energy" requirement by virtue of the fact that the conduction efficiency decreases as the currents are farther removed from infinite values. Decreasing currents cause an increase in (1) the combined electrode falls, and (2) the surface losses per unit volume of the discharge column, which collectively represent the "excess energy" requirement of $B/I^n$ watts per unit current.

3. These energy requirements per unit current combine to represent the voltampere characteristics. The functioning of the "excess energy" term $B/I^n$ *explains* the falling slope of the characteristics, and the so-called

"negative" resistance of the electric arc. In other words, the net efficiency of the arc increases with current.

4. The current exponent $n$ indicates the rate at which the arcs approach "infinite current" conditions. As $n$ is proportional to the anode temperature, this temperature appears to influence the ionization and absorption properties of the positive column, and therefore regulates the efficiency of these processes. On this basis, the high temperature arcs are the most efficient.

5. The largest portion of the "excess energy" losses probably result from heat and light radiation and ionic diffusion from the arc stream. There is evidence that this radiation and diffusion come from a cylindrical layer of the arc stream whose depth is inversely proportional to the gas temperature, so that in spite of the slightly increased surface of high temperature arcs their efficiency is still higher than for low temperature arcs.

6. In high current arcs there are considerable portions of the discharge which do not contribute to the surface losses. In falling through the electric field the ions in this non-radiating, high efficiency portion may acquire an extra energy over those near the surface. Under the effect of the directed field they would contribute this extra energy as heat to the electrodes. Energy equilibrium conditions at the welding arc cathode make such a suggestion plausible.

These studies tend to unify some general conclusions from seemingly unrelated experiments in giving a more complete physical picture of the arc discharge. Certain concepts should be useful in bringing theory and practise into better agreement, and enabling proper application of the arc in commercial problems. Above all, the need for correlated measurements on the arc discharge is emphasized.

The author is particularly grateful to Professor Doan of Lehigh University under whose guidance and direction these studies have been carried out, for his interest and encouragement in the work; to Professor Hertz for laboratory facilities at the Charlottenburg Technishche Hochschule, and to Engineering Foundation whose support made these studies possible.

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## Discussion

**A. R. Miller:** In this paper Mr. Myer starts with an equation which has withstood the criticism of students of arc theory for some time, and attempts an explanation of the equation starting from an energy point of view. This is somewhat analogous to a practise among electrical engineers when discussing circuit problems such as transient conditions, whereby energy is assumed to be dissipated or transferred, in contradistinction to speaking of these things in terms of voltages. However, there seems to be a fundamentally logical procedure in this instance when discussing the arc phenomena, in that it attaches some meaning to the various terms of the equation. The equation referred to ($V = A + BI^{-n}$) and its predecessors seemed to have been devised as an equation to fit a curve plotted from experimental data, without any recourse to reason. This sufficed for many engineering purposes however. Since then many have tried to explain the various terms (or even other forms of equations for the same phenomena) in various ways and by various means.

Myer finds discrepancies in his point of view, in much the same way as others have found shortcomings in theirs.

Various theories are in existence in regard to arc phenomena. Thus some[1] explain a part of it on the assumption of thermionic forces, which may quite agree with certain conditions, and which certainly play a part in arc theory. Others[2] seem to think that the electric field has considerable to do with it; in fact under certain conditions, as in vacuum tubes, it may be the important factor. In any case it can hardly be doubted to be a combination of the two. Other mechanism must also be considered, as for instance the surrounding medium. All of these factors are taken care of in a collective way in the "energy" method of approach. By any route the explanation is a difficult one hampered by many factors to be controlled.

It seems that one line of attack which has as yet received little attention, but which might supply other lines of thought is the phenomena which occurs in very short time intervals upon the establishment of the arc, or in its variation. There is available at present the cathode ray oscillograph which enables the measurement of currents and voltages of very short time intervals and might be useful in verifying some of the ionization theories supposed to play a role in arc-phenomena. Such studies can be carried out with the equipment in many electrical engineering laboratories.

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[1] Compton.
[2] Langmuir.

# Transients In Arc Welding Generators

## With Experimental Verification

BY A. R. MILLER*

Associate, A.I.E.E.

***Synopsis.***—*This paper gives a mathematical analysis of armature and field transients in d-c generators of the type used in arc welding. The analysis is reduced to the simplest form, and is exact, under the premises given. Armature and field currents only are treated, and comparisons between calculated and experimental graphs are shown.*

DURING the last few years a great deal of study has been given to the design of d-c arc welding machines with a view of obtaining more desirable characteristics under transient conditions. To this end several types of construction have been employed, as for example, the neutralized and transformer-coupled welders. The latter have been designed in several different ways, and the question of their electrical principles has been discussed. Recently tests have been made on a generator so connected, and an attempt was made to predict the important features of its operation under transient conditions. The results of such an investigation have been embodied in this paper.

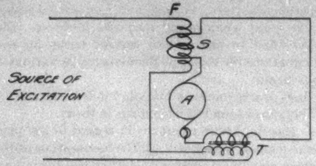

FIG. 1—WIRING DIAGRAM

S = series field
A = armature
F = shunt field
T = transformer

The transient solutions of currents in d-c machines have been made before, but these have mainly considered the theoretical side only, and have dealt almost wholly with currents in the armature and field circuits. With the addition of transformer connections between the field and armature circuits, and also because certain characteristics are desired when the current changes from one value to another as in welding, more complete solutions are desirable.

### ASSUMPTIONS USED IN MAKING CALCULATIONS

When applying electrical circuit theory to arc welding machines, certain simplifying assumptions can usually be made. These are as follows:

1. The excitation of the field is from a constant voltage source. While there are exceptions to this, it is for almost all cases quite general. The machine for which the oscillograms are shown and for which the calculations were made had constant excitation from a battery, with a view towards simplifying the calculations.

2. The magnetic circuit of the machine had small eddy current effects, and magnetic saturation did not exist. For present arc welding generators these assumptions are quite legitimate, since the magnetic circuits are usually laminated, and the voltages under operation are but a fraction of the maximum possible voltage.

3. The series and shunt fields are differentially connected, magnetically, to each other.

4. Rotational speed of machine constant under all loads.

A diagrammatic sketch of a d-c generator with a transformer connection between armature and field circuit is shown in Fig. 1.

### INTERPRETATION OF SOLUTIONS

It might be of advantage to show the method of obtaining the graphs, which are shown in comparison with the oscillograms, in that it may be helpful when interpreting the meaning of several factors which enter into the calculation of the currents.

The solution for the armature current, taking as an example a machine without reactor or transformer coupling between field and armature circuits, is given by the following equation.

$$i_1 = 75 + 660\,\epsilon^{-49.8t} - 735\,\epsilon^{-101.2t} \qquad (8)$$

The plotting can be done most readily by drawing the three component parts, and then adding graphically as shown in Fig. 2. For example, values of time required to give the exponential factor of 75, 50, 25 and 5 per cent of the coefficient can be obtained and each curve plotted, then added. By so doing, it is seen that the recovery to steady state is dependent upon the term having the smaller exponential factor. The amplitude of the component also has its effect, of course. The time at which the currents are at a maximum from the normal or steady state condition is largely determined by the term having the larger exponential constant, and consequently the amount of overshooting which will occur. Hence, from the tabulated values of the coefficients and exponential factors for the various components, it is quite possible to approximate very closely the amount of overshooting and the time to recover to any percentage of normal value, without the more laborious method of plotting out the equation.

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., Jan. 23-27, 1933.*

## EXPERIMENTAL VERIFICATION OF SOLUTIONS

Certain typical oscillograms for which solutions have been obtained are shown in Figs. 3, 4, 5 and 6. Equation (7) (Appendix A) has several typical solutions, depending upon the magnitude and sign of the quantity under the radical.

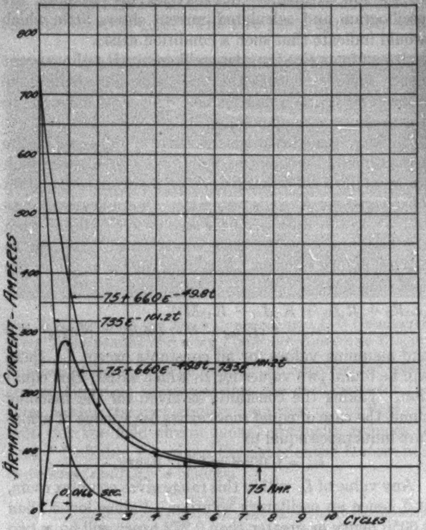


FIG. 2—COMPONENT PARTS OF A SOLUTION

Calculated graph of armature current for Fig. 3
° Values from oscillogram—Fig. 3

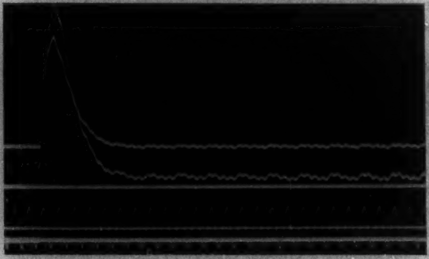
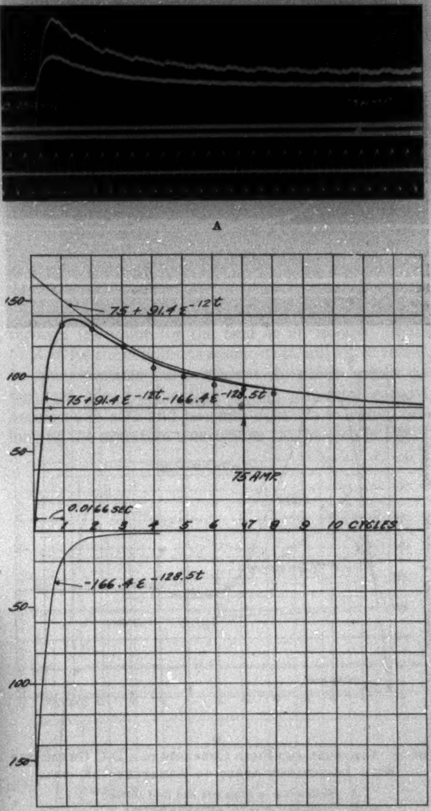


FIG. 3—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR—NO EXTERNAL INDUCTANCE

Fig. 3 was obtained under a condition which gave to this radical a positive value, the solution in this instance becoming, for the armature current (Appendix A)

$$i = 75 + 660\,\epsilon^{-49.8t} - 735\,\epsilon^{-101.2t} \qquad (9)$$

A plot of this equation is shown in Fig. 2. There results an overshooting of the steady-state value of both field and armature currents. This condition will obtain for all values which the radical may have, except for one case to be mentioned later. As the value of this radical, while remaining real, is decreased, the two roots approach each other in value, since one is the sum and the other the difference of the two terms.



A

B

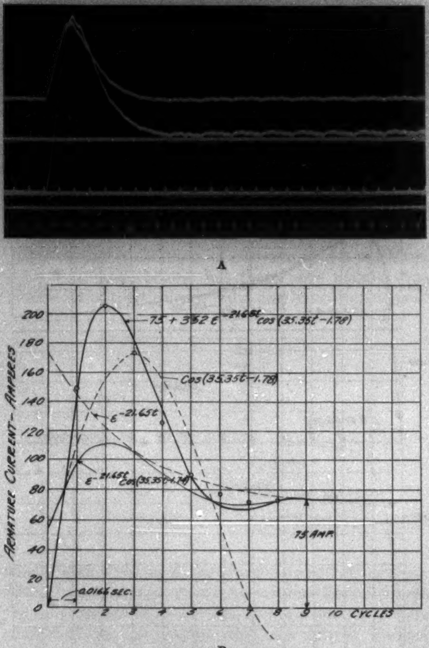
FIG. 4—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR WITH SHUNT FIELD INDUCTANCE ADDED EXTERNALLY

A. Oscillogram of armature and field current
B. Calculated graph of armature current
° Values from oscillograms

There are of course particular values for which the radical is zero, and only one distinct root then results. This is sometimes said to be a case of equal roots. As this condition is approached, the coefficients of the transient terms become larger in magnitude, but the difference will always be such as to make the current overshoot the normal value, and will have a definite value.

Experimental verification of the above discussion is obtained in Figs. 3 and 4. In Fig. 3 the radical contains two terms which are relatively alike in value, while in Fig. 4 these roots are considerably separated. The latter condition was obtained by adding inductance to the field circuit. The equation for the armature current in Fig. 4 is

$$i_1 = 75 + 73\,\epsilon^{-9.9t} - 143\,\epsilon^{-189.5t} \qquad \textbf{(10)}$$


A

B

FIG. 5—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR WITH INDUCTANCE ADDED TO ARMATURE CIRCUIT

A. Oscillogram of armature and field current
B. Calculated graph of armature current
° Values from oscillogram

The plot of the component parts of equation (8) as shown in Fig. 2 has for the component terms values much in excess of those in Fig. 4B.

If the value under the radical is made negative, as for example by increasing the negative term under the radical, the roots become imaginary, and the solution is oscillatory in so far as its form is concerned. The oscillogram shown in Fig. 5A was taken under conditions such that there results negative roots, brought about by increasing the inductance of the armature circuit. The equation for the armature current is (see Appendix A):

$$i_1 = 75 + 336\,\epsilon^{-21.7t}\cos(33.3t - 1.78) \qquad \textbf{(11)}$$

The terms with imaginary coefficients have been converted to a cosine function. Due to the large decrement in the coefficient of the cosine term, and also to its low frequency (5.14 cycles per second), the oscillogram and calculated current shows little which would indicate that such a condition exists.

It can be noticed on the oscillogram that the current curve slightly touches the line below just before the current settles to a final value. This is perhaps due to the oscillatory component.

An interesting feature is the range of values which the inductance of the armature circuit may have, over which an oscillatory solution exists. By referring to equation (7) (Appendix A), it is noted that the radical will contain a negative number, if the second term is larger than the first; the roots are then complex, and give rise to the oscillatory solution. Equating the terms under the radical to zero,

$$(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)^2 - 4\,(L_1L_2 - M^2)\,(R_1R_2 + K_{11}R_2) = 0$$

and assuming values for all constants except $L_1$, there will be found two values for $L_1$ which satisfy this equation. Taking the constants as given for the machine alone, the case of equal roots exists for a value of armature inductance equal to

$$L_1 = 0.0056 \text{ or } 0.272 \text{ henry.}$$

Any value of $L_1$ within this range gives complex roots, and hence an oscillatory solution. Values lower than 0.0056 henry or greater than 0.272 henry will have two real roots. Thus in the oscillogram cited above, when $L_1 = 0.0045$ henry (Fig. 3) there results two real roots; when $L_1 = 0.0075$ henry (Fig. 5) there are complex roots, the latter being in the range of values given above.

From the preceding discussion, it is evident that the case of equal roots, so called, is merely a borderline between solutions having real and imaginary roots, and for quite a large range of values the actual current variation obtained is quite similar. The values of armature inductance used in these tests were quite close to the lower limit, and give graphs of current which have similar characteristics. This is in agreement with what would be expected, as the inductance is gradually increased, as was done in this case, there would be only a gradual change in the magnitude and shape of the current as shown on an oscillogram.

The introduction of an interconnection between the armature and field circuits by means of a transformer gives some interesting results. In this manner it is possible, if the transformer is properly designed, to neutralize the effect of the mutual inductance between the series and shunt field coils within the machines by means of that in the transformer. Experimentally, complete neutralization was not obtained, but the mutual inductance was reduced from 0.3 henry to approximately 0.2 henry. An oscillogram of the armature and field current is shown in Fig. 6, and the calculated armature current in Fig. 7.

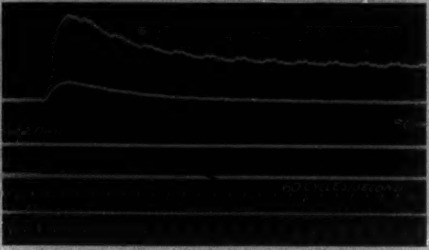


FIG. 6—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR WITH TRANSFORMER BETWEEN FIELD AND ARMATURE CIRCUIT

The most peculiar phenomena which exists in this case is the manner in which the two transient terms in the solution behave as the total mutual inductance is reduced towards zero. The two roots approach as a final value the roots which would be obtained for either circuit alone; at the same time the coefficient for the term having the root approaching that of the field circuit (for the field circuit alone) gradually reduces to zero. In Table I is given the exponential factors and the corresponding coefficients.

TABLE I

| $M$ | $a_1$ | $A_1$ | $a_2$ | $A_2$ | $I$ |
|---|---|---|---|---|---|
| 0.2 | −7.40 | 42.8 | − 78.7 | 117.8 | 75 |
| 0.1 | −5.84 | 16.0 | − 89.5 | 91 | 75 |
| 0.05 | −5.32 | 7.5 | − 96.5 | 82.5 | 75 |
| 0 | −4.86 | 0 | −104.5 | 75 | 75 |
| −0.1 | −4.07 | −12.0 | −118.5 | 63 | 75 |

Solution: $i_1 = I + A_1\epsilon^{a_1 t} - A_2\epsilon^{a_2 t}$

Mathematically, equation (7) (with $M = 0$) reduces to

$$\frac{-L_1R_2 + (R_1 + K_{11})L_2 \pm \sqrt{[L_1R_2 - (R_1 + K_{11})L_2]^2}}{2\,L_1L_2}$$

which gives, in the limit,

$$-\frac{2\,L_1R_2}{2\,L_1L_2} \text{ or } -\frac{R_2}{L_2} \text{ as one root, and}$$

$$-\frac{2\,(R_2 + K_{11})L_{12}}{2\,L_1L_2} = -\frac{(R_1 + K_{11})}{L_1} \text{ as the other.}$$

Fig. 7 has a mathematical plot for the condition of $M = 0$, by way of comparison.

The physical interpretation of this case is not difficult to understand. With no mutual impedance between the circuits, one current cannot react upon the other; in other words, the transient current acts as if in a circuit far removed under these conditions.

If the mutual inductance of the transformer is larger than that of the machine, the above solutions still hold, $M$ becoming negative in value. One solution under these assumptions for armature currents is shown graphically in Fig. 7. The rate of rise in the armature current is much reduced, and a plot of the field current would under these conditions show a decrease instead of an increase of current just after short circuit, as would be expected.

The above case of zero mutual inductance suggests the nature of the two exponential factors which are contained in the solution of the currents. The larger exponential factor appears to be due to the armature circuit, as modified by the field circuit; the smaller factor in turn due to the field, as modified by the armature circuit.

By reference to Table I the nature of the variation of the exponential factors and the corresponding coefficients can be observed. $a_1$ is the exponential factor pertaining to the field circuit, and $A_1$ the coefficient of the corresponding transient term. As the mutual inductance is lowered the exponential factor decreases through the value for the field as an isolated circuit (− 4.86 for the conditions assumed) to still lower values. In the meantime the coefficient $A_1$ which largely determines the overshooting of the armature current, decreases to zero and becomes negative in value, prolonging the armature transient as can be seen in Fig. 7.

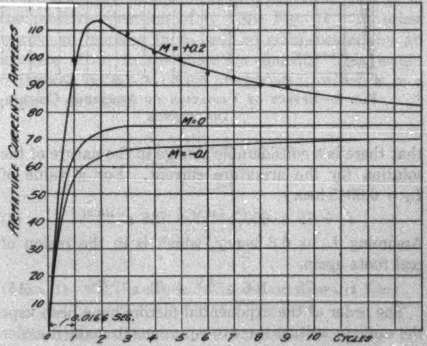


FIG. 7—ARMATURE AND FIELD CURRENTS WITH $M = 0$ AND $M = -0.1$

Upper curve—calculated graph for Fig. 6
° Values from oscillogram

The exponential factor $a_2$ which is that of the armature circuit as modified by the field, continually increases in value, while the corresponding coefficient decreases. The net effect is, compared to that of this term when $M$ is positive, to decrease the rate of increase of the armature transient current.

A comparison of the results obtained by inserting inductance in the armature circuit is shown in Fig. 8 below. These graphs were calculated under the assumption that all circuit constants except armature self-inductance remained fixed. The graphs for 0.0045 and 0.007 henry inductance are experimentally verified in Fig. 3 and Fig. 5.

If the value of the armature inductance is increased beyond the range of values giving complex roots (0.00563 henry to 0.272 henry) it is interesting to note that there is a considerable change in the nature of the solution for the armature current. For a value of $L_1 = 0.0045$ henry,

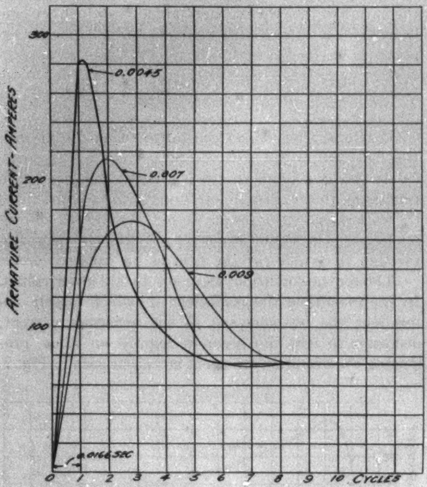


FIG. 8—EFFECT OF VARIATION OF ARMATURE CIRCUIT INDUCTANCE

$$i_1 = 75 + 660\ \epsilon^{-49.8t} - 735\ \epsilon^{-101.2t} \qquad (8)$$

Assuming $L_1 = 0.3$ henry, which is in the region of real roots again,

$$i_1 = 75 - 106\ \epsilon^{-3.5t} + 31\ \epsilon^{-6.28t} \qquad (15)$$

The order of the exponential factors have been kept the same in writing the two equations to make it easier to compare the coefficients. It will be noted the coefficients have changed order in relative magnitude, as well as in sign. That is, before entering the complex root region, the larger coefficient went with the larger exponential factor, and was negative in value; when leaving this region exactly the reverse conditions exist.

As the inductance is varied over the range of values giving oscillatory solutions, the frequency of the oscillations becomes less as higher values of inductance are used and the exponential factor becomes smaller in magnitude, as does the coefficient of the cosine term. That is, there is a less rapidly varying current for an armature transient, and it lasts over a longer interval of time.

Thus, with 0.0075 henry inductance in the armature the current is

$$i_1 = 75 + 336\ \epsilon^{-21.7t} \cos{(33.3t - 1.78)} \qquad (11)$$

and with 0.2 henry assumed, it is

$$i_1 = 75 - 90.7\ \epsilon^{-5.01t} \cos{(2.915t - 0.6)} \qquad (16)$$

## FIELD CURRENT

Only one solution for the field current is given. This matter is of minor importance as far as currents are concerned. In Fig. 9 a graph is plotted for the field current shown in the oscillogram in Fig. 3. The current in this instance is (equation (**9**), Appendix A)

$$i_2 = 0.96 + 8.73\ \epsilon^{-49.8t} - 8.73\ \epsilon^{-101.2t} \qquad (9)$$

The field current may become of importance in the calculation of voltages in various parts of the machine, but that matter, together with others, is reserved for a future paper.

In the oscillograms which are shown a considerable amount of superimposed ripples will be noted in the current. In some instances, as on the rapidly rising portion of the current graph, this has made the matter of scaling the oscillograms inaccurate. As far as possible an average value has been taken. The calibration of the films was obtained from the steady-state portion, which was read by a d-c ammeter during the tests. Hence, in using this portion, an average value of the ripple was assumed to be correct.

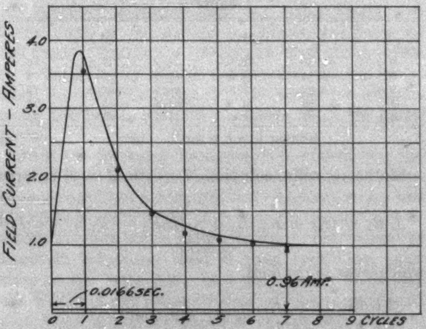


FIG. 9—FIELD CURRENT IN D-C GENERATOR WITH NO EXTERNAL FIELD OR ARMATURE INDUCTANCE

° Values from oscillogram

While the above tests were made on arc welding generators, the conclusion must not be drawn that the results represent typical conditions. The constants of the generators were changed in such a manner as would best demonstrate the possibility of making calculations for unique circuit conditions. As a matter of fact the machines as originally designed perform very satisfactorily under operating conditions.

The above investigation shows that it is possible, once the proper design constants are known, to predetermine the currents in an arc-welding generator due to circuit changes. It seems, on the basis of the above, that it should be possible to lay down without much difficulty a standard method of testing to determine the machine constants and a standard calculation schedule from which the most important points in the welder characteristics could be determined.

Acknowledgment is made of the assistance in the experimental work and the preparation of the material for this paper of Professor F. Creedy, Mr. E. C. Easton, and Mr. F. B. Lucas of the Electrical Engineering Department of Lehigh University.

## List of Symbols

$R_1$ = resistance of armature circuit.

$R_2$ = resistance of field circuit.

$L_1$ = self-inductance of armature circuit, including the armature winding, series field, and any reactor or other device which may be in that circuit.

$L_2$ = total self-inductance of the field circuit.

$M = M_{12} = M_{21}$ = mutual inductance between the armature and field circuit. Saturation is assumed negligible.

$K_{12}$ = rotation voltage constant between shunt field current and voltage induced by the rotation of the armature in the magnetic field produced by the field current.

$K_{11}$ = rotational voltage constant for the series field current.

$E$ = open circuit (or induced voltage) produced by the field current prior to a transient condition in the armature.

$p = d/dt$.

$t$ = time in seconds.

## Appendix A

### ARMATURE AND FIELD CURRENTS

During transient conditions in a compound wound generator, there are voltages due to the following causes:

1. Rotational voltage due to field current.
2. Rotational voltage due to armature current in series field.
3. Voltages in either circuit by virtue of the mutual inductance between the armature and field circuits due to the variation in the other.
4. Voltages in each circuit produced by the self-inductance of each circuit from the change of current in that circuit.
5. Voltages due to resistances in either circuit.

Fig. 10 shows a diagrammatic sketch of the equivalent circuit of a differentially connected arc-welding generator.

Assuming the positive directions of currents to be as shown, then

$$E - (R_1 + K_{11} + L_1 p)\, i_1 + (K_{12} + Mp)\, i_2 = 0 \qquad (1)$$

for the armature circuit.

This is a statement of the condition for voltage relationships in a closed armature circuit. $E$ is the voltage produced in the armature circuit by the field current prior to short-circuit, and is assumed constant. Consequently $i_2$ is the change in value from that initially existing in the field circuit.

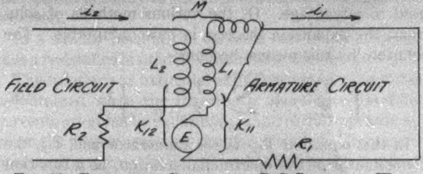


FIG. 10—EQUIVALENT CIRCUIT OF A D-C GENERATOR WITH SEPARATELY EXCITED FIELD

When the armature current is flowing in a positive direction, the series field flux in a differential wound compound machine opposes the main field flux; hence the minus sign with $K_{11}$. Any increase in a positive direction of the field current produces a voltage in the same direction in the armature circuit as the voltage $E$, which gives to $K_{12}$ a plus sign. Also, any positive rate of change of the field current will produce a voltage in the armature circuit in the direction of $E$; that is, in the positive direction of $i_1$. See Fig. 11. In other words, an increase in $\phi_2$ will be compensated by an increase of $\phi_1$ in the direction shown. This would require an induced voltage producing $i_2$, which is in a positive direction.

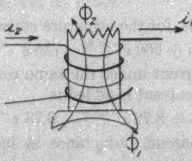


FIG. 11—RELATIVE DIRECTIONS OF ARMATURE AND FIELD CURRENTS ABOUT FIELD POLE

The differential equation for the field circuit is,

$$Mpi_1 - (R_2 + L_2 p)\, i_2 = 0 \qquad (2)$$

These equations solved simultaneously for $i_1$ and $i_2$ give the following results.

$$i_1 = \frac{(R_2 + L_2 p)\, E}{(R_1 + K_{11} + L_1 p)\,(R_2 + L_2 p) - (K_{12} + M\,p)\,(Mp)} \qquad (3)$$

$$i_2 = \frac{Mp\, E}{(R_1 + K_{11} + L_1 p)\,(R_2 + L_2 p) - (K_{12} + M\,p)\,(Mp)} \qquad (4)$$

It must be remembered that the latter gives only the change in value of the field current from that required to produce $E$ on open circuit; in other words, from the field current prior to short circuit.

The denominator in equations (**3**) and (**4**) above, when multiplied out and terms collected according to the powers of $p$ is

$$(L_1L_2 - M^2)\, p^2 + (L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)\, p + (R_1R_2 + K_{11}R_2) \qquad (5)$$

In this particular study operational calculus can be used to advantage. Of the various methods of solutions, the expansion theorem is most adaptable. The solution, by this means, becomes

$$i = \left[ \frac{Y_{(0)}}{Z_{(0)}} + \sum_{p = p_1}^{p = p_n} \frac{Y_{(p)}\, \epsilon^{pt}}{Z_{(p)}'\, p} \right] E \qquad (6)$$

In this equation $Y_{(p)}$ is the numerator and $Z_{(p)}$ the denominator of the operational solution, as a function of $p$. $Z_{(p)}'$ is the function obtained by differentiating $Z_{(p)}$ with respect to $p$. $p_1 \ldots p_n$ are the roots of $Z_{(p)}$. $Z_{(p)}$ for the armature and field currents is given by equation (**5**) above.

Accordingly $\dfrac{Y_{(0)}}{Z_{(0)}} = \dfrac{E}{R_1 + K_{11}}$ for the armature current, and 0 for the field circuit.

Also

$$p_{1,2} = \frac{-(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M) \pm \sqrt{(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)^2 - 4\,(L_1L_2 - M^2)\,(R_1R_2 + K_{11}R_2)}}{2\,(L_1L_2 - M^2)} \qquad (7)$$

For a particular generator, without transformer or armature circuit reactor, $R_1 + K_{11} = 0.70$; $K_{12} = 55$; $L_1 = 0.0045$; $L_2 = 27.9$; $R_2 = 260$; $M = 0.3$; $E = 53$; $I_f = 0.96$.

The solution is, for the armature current

$$i_1 = 75 + 660\, \epsilon^{-49.8t} - 735\, \epsilon^{-101.2t} \qquad (8)$$

and the field current under the same conditions, when the intital field current is added is

$$i_2 = 0.96 + 8.73\, \epsilon^{-49.8t} - 8.73\, \epsilon^{-101.2t} \qquad (9)$$

If the field circuit inductance is increased to 50 henrys,

$$i_1 = 75 + 73\, \epsilon^{-9.9t} - 143\, \epsilon^{-189.5t} \qquad (10)$$

When the armature circuit has its inductance increased to $L_1 = 0.0075$ henrys, and the field circuit inductance restored to the first value, then

$$i_1 = 75 + 336\, \epsilon^{-21.7t} \cos(33.3t - 1.78) \qquad (11)$$

If the transformer is added

$L_1 = 0.006$; $L_2 = 45.0$; $R_2 = 243$; $M = 0.2$

The equation for armature current under these conditions is given by

$$i_1 = 75 - 166.4\, \epsilon^{-128.5t} + 91.4\, \epsilon^{-12.0t} \qquad (12)$$

The first cases, given by equations (**8**), (**9**) and (**10**), are cases of real roots; the second, given by equation (**11**), a condition giving complex roots; and the latter, equation (**12**), an approach to a solution having two roots, only one of which will have a coefficient in the limit, when $M = 0$.

## Appendix B

### SUDDEN CHANGE IN THE ARMATURE CIRCUIT RESISTANCE

During the process of welding there is the equivalent of a change in the resistance of the armature circuit, when the distance between the electrodes is changed, or when the electrodes come into contact with each other. Fig. 12 shows a diagrammatic sketch of a d-c generator with the resistance in two sections in the armature, one of which can be short-circuited by a switch. Closing the switch is equivalent to removing the resistance from the armature circuit. The initial condition, that is, prior to closing the switch, is that there exists a certain current in the armature circuit, as determined by the condition just prior to removing the resistance.

The operational processes used in the solution in Appendix A assume no current as an initial condition. However, in a circuit having linear voltage-current relationships as the one considered, solutions can be superimposed.

As far as the circuit is concerned, instead of the short-circuiting switch, suppose a battery is applied in such a direction and of such a magnitude as to reduce the current in the short-circuited resistance instantly to zero, which becomes equivalent to closing the switch. This is performed electrically by connecting a battery as shown by the dotted lines; the armature and field currents produced give the change in their respective circuits.

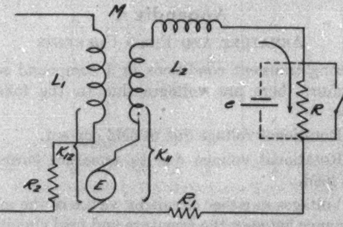


FIG. 12—EQUIVALENT CIRCUIT FOR SUDDEN CHANGE OF ARMATURE CIRCUIT RESISTANCE

This voltage would be

$$e = I_1R$$

where $I_1$ is the current initially in the short-circuited resistance $R$.

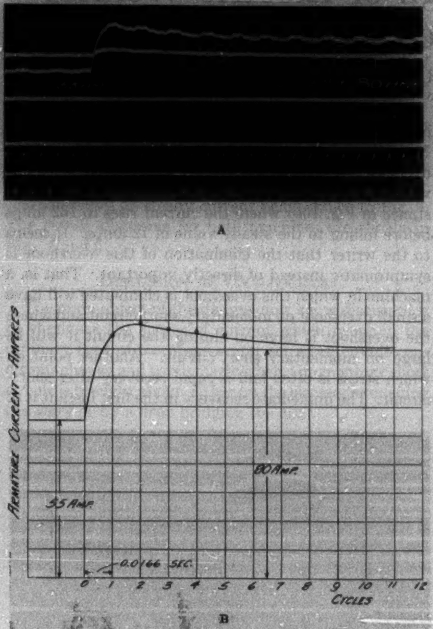


Fig. 13—Armature and Field Currents When Armature Circuit Resistance is Changed

A. Oscillogram of armature and field currents
B. Calculated graph of armature current
• Values from oscillogram

The equations for the change of current in armature and field circuit become

$$i_1 = \frac{(I_1R)\,(R_2 + L_2p)}{(R_1 + K_{11} + L_1p)\,(R_2 + L_2p) - (K_{12} + Mp)\,(Mp)} \tag{13}$$

$$i_2 = \frac{(I_1R)Mp}{(R_1 + K_{11} + L_1p)\,(R_2 + L_2p) - (K_{12} + Mp)\,(Mp)} \tag{14}$$

These currents, added to those previously existing, give the current actually in the circuit after the resistance is removed.

In a similar fashion the currents can be obtained in case a resistance is suddenly inserted in the circuit.

The solutions as indicated above are exactly the same as obtained when the machine is short-circuited; the currents are given by equations (3) and (4) in Appendix A, when the proper armature resistance is used. The graph of armature current in Fig. 13 is obtained in this fashion.

It is the contention that those machines having the smaller transient armature currents produce the better welding. The momentary change in the equivalent resistance of the circuit produces the transients as described above, and if the momentary change lasts sufficient time, would go through the same cycle. Consequently, if circuit conditions remain otherwise the same, a generator having the smaller overshoot in current on short-circuit would be the more desirable, and the study of these short-circuit currents has a direct relationship to the operating characteristics of the machine.

## References

1. *Design of Constant Current Generators for Arc-Welding,* K. L. Hansen, A.I.E.E., Vol. 39, p. 1357.

2. *The Neutralized Welder—A Means of Controlling Transients,* F. Creedy, A.I.E.E., Vol. 50, p. 662.

# Performance and Design of Electric Welders With Controlled Transients

BY F. CREEDY*
Member, A.I.E.E.

IT HAS been evident to engineers for some years past that the transient currents and voltages which occur due to the rapid changes taking place in the welding circuit should be minimized in order to get the best possible operation. Several types of apparatus have been built and tried out in practise in which these transients have been reduced and the verdict of the practical welder, both in this country and Europe, has been that such apparatus is more steady in operation than the older type of apparatus in which transients were not minimized. This is how the matter stands at the present moment. The belief in the advantages of minimizing the transients rests essentially on the verdict of the practical welder. Our first task, therefore, must be to translate this verdict into the language of the electrical engineer so that a perfectly definite problem expressed in his own language is placed before the designer of welding generators. One type of the new apparatus differs from the old only by means of a transformer interlinking field and armature circuit and so connected as to minimize or abolish the mutual induction between the two. It is easy, therefore, to test such a machine with and without the transformer, equivalent impedances being substituted where the transformer is not used.

Oscillograms of welding current show that the voltage frequently drops to zero when the arc is short-circuited by a drop of molten metal, there being usually a corresponding rise of current at this moment. One of the most important tests, therefore, would seem to be an oscillogram of a momentary short circuit on the generator. This can easily be arranged by connecting a switch across the terminals in series with a circuit breaker. As soon as the switch is closed the circuit breaker begins to carry a heavy current and accordingly opens. The result of such a test is shown in Figs. 1A and 1B in which *A* is the welding current, *D* the field current and *C* the volts across the short circuit. It will be seen that at the instant of short-circuit the volts drop to zero and remain there for about 5 cycles after which the circuit breaker trips and the voltage is restored.

Fig. 1B shows the machine without correcting transformer and Fig. 1A with transformer. It will be seen that the peak of current which occurs in 1B has been wiped out by the action of the transformer. This, in the writer's opinion, is the most useful effect produced by these devices for minimizing transients and in these oscillograms it is expressed in the language of the electrical engineer so that we are entitled to say that steady welding means absence of variation in the welding current. Much stress is frequently laid on the elimination of the overshoot, a peak of current which is found when the welding circuit is closed from open circuit (as for instance in Fig. 10C) where the current rises to 162 amps before falling to the steady value of 72 amps. It seems to the writer that the elimination of this overshoot is symptomatic instead of directly important. That is, a machine in which this overshoot is eliminated will have a small overshoot on momentary short circuit and where the overshoot is large on closing the circuit it will be large on momentary short circuit. Another point on which stress is often laid is rapid recovery after short-circuit. The immediate recovery in the first instant is of course provided by the discharge of the reactance (as shown for instance in Fig. 11A). But when the reactance has fully discharged, the voltage may fall to an unduly low value from which it only slowly recovers. This reduction is due to the fall of the field current shown at *D* and it is this fall after the reactance has discharged that we desire to eliminate. This is done in Fig. 10A, where it will be seen that the field current drops very much less than in Fig. 11A taken under exactly the same conditions and consequently the voltage *C* does not drop off so much.

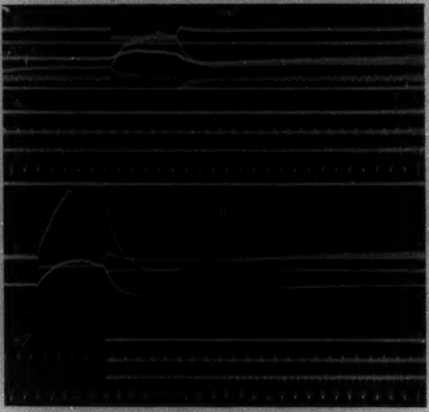


Fig. 1—Momentary Short Circuit With and Without Reactor Transformer

These are some of the benefits to be obtained by eliminating transients which, especially the former, are extremely important in practise.

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*Lehigh University.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

The following investigations were made by means of two machines. (1) A "neutralized welder" of the type discussed in the writer's former paper* and a welder of standard design to which it was possible to apply a transformer in order to reduce the mutual induction between armature and field. This is referred to below as "the second machine." A photograph of the first machine is shown in Fig. 2 (which, incidentally shows the first American-built binary converter), its voltampere characteristics on steady current being shown in Fig. 3. The circuit diagrams for both machines are shown in Figs. 4 and 5.

## DISCUSSION OF OSCILLOGRAMS

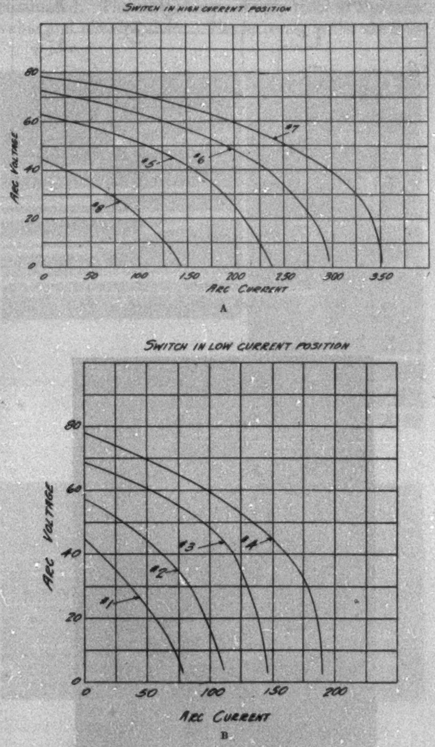
The main object of the designs now being discussed is to eliminate the surges of current which occur in the ordinary type of motor-generator set when circuit conditions change and particularly when a momentary short circuit is brought about, either by the electrode touching the work or by a drop bridging the arc.

FIG. 2—THE NEUTRALIZED WELDER

In Fig. 6A is shown the effect of the momentary short circuit in the neutralized machine, *A* being the current, zero line *B*, *C* being the voltage and *D* the field current.

Fig 6B is a similar curve for a standard type of welder (referred to as "the second machine"). At the bottom is shown a 60-cycle timing wave so that the distance between nieghboring maxima is 1/60 of a second. These are perhaps the most striking oscillograms of the series. They show that in the neutralized machine the maximum increase of current, when an arc across which there is a drop of about 20 volts is short-circuited, is about 33 per cent whereas the corresponding rise in the second is 100 per cent. This means that in the neutralized machine the power flow is increased in the ratio of 1 to 1.76 while in the other it is increased in the ratio of 1 to 4.

The next series show the effect of a permanent short circuit suddenly applied to the machine when carrying 150 amperes and about 20 volts. Two things are noticeable in Fig. 7A which represents the neutralized machine; *A* being the current as before with zero line *B*, *C* the volts, and *D* the field current. The short circuit is applied at the left and it will be seen that the current rises about 33 per cent and then gradually settles down again to its original value. This is because the machine is so designed as to have a constant current characteristic for slow variations as is shown by its voltampere characteristic curves, (Fig. 3). Consequently after it has been given time to adjust itself, the current after short circuit is the same as before.



A

B

FIGS. 3A AND 3B—VOLTAMPERE CHARACTERISTICS OF NEUTRALIZED WELDER

Fig. 7B represents the second machine and again two things are noticeable. Starting with 150 amperes and 20 volts as before, when the short circuit is applied the current rises to about double its original value (power multiplied 4 times) and then after about 16 or 17 cycles of the timing wave falls to a value of 1.55 times the original. Thus in such a machine the effect of a permanent short circuit is a double one. (a) It causes a surge of about 100 per cent in excess of normal and (b) it causes a permanent rise of current of about 55 per cent in excess of normal unlike the neutralized machine where the final current is the same as the initial current.

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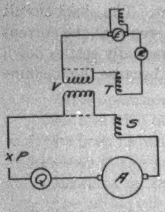
*The *Neutralized Welder*, by F. Creedy, A.I.E.E. TRANS., June 1931, p. 662.



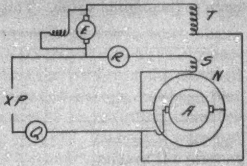


Fig. 4—(Left) Separately Excited Welder
Fig. 5—(Right) Neutralized Welder

*A* armature
*N* neutralizing winding
*S* series coil
*T* shunt and/or separate excitation
*E* exciter
*R* regulating rheostat
*Q* reactance
*P* arc
*V* transformer (dotted lines show how it may be cut out)

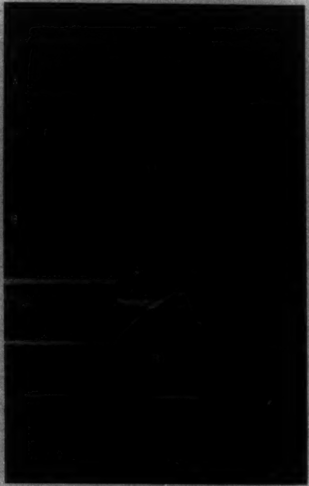


Fig. 6—Momentary Short Circuits on Two Different Machines

Machines with constant-current characteristics are by no means new, of course, but the present design eliminates the disadvantages of older constant-current machines by enormously reducing the self-induction of the shunt-connected coil, thus enabling it to follow rapid variations in a way the older types could not.

The next curves show the effect of suddenly opening the circuit.

Fig. 8a shows the effect of suddenly opening the circuit on the neutralized machine. *A* being the current, zero line *B*, *C* the voltage, and *D* the field current; *E* being the voltage directly across the brushes. It will be seen that when the current stops, the first effect is a rapid rise of voltage due to the discharge of the reactance, the voltage momentarily rising to a value considerably higher than normal. The voltage then falls to normal and continues at a constant value apart from small oscillations due to the generator teeth, etc. Meanwhile the field current has risen to the new value corresponding to the higher voltage of the circuit and this takes approximately 2½ cycles of the timing wave or 0.04 seconds.

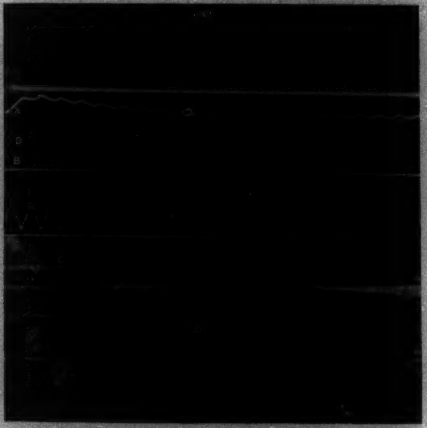


Fig. 7—Permanent Short Circuits on Two Different Machines

Fig. 8b is a similar curve in which the same phenomena are shown to a larger scale. The most important thing to notice is that by the time the current has reached zero, the voltage has risen up to or beyond the open-circuit value. This is true of any machine which has a large reactance as will be seen in a moment. But the special feature of this machine is that by the time the reactance has finished discharging the machine has picked up its voltage so that it is able to maintain it constant after this. In this oscillogram as stated *C* is the voltage across the terminals while *E* is the voltage across the commutator of the machine that is without taking the reactance into account. This voltage is nearly proportional to the field current and the rapid rate of growth should be noted.

Fig. 8C gives the corresponding series of curves for the second machine, *A*, *B*, *C*, *D*, and *E* having the same meaning as before. Here we see the same kick of voltage when the current suddenly stops and the reactance discharges, but when the reactance has discharged the machine has scarcely begun to pick up its voltage and it will be seen that the voltage curve *C* is slowly rising as we proceed towards the right and after 14 cycles or 0.23 seconds it is found not yet to have reached the steady state.

The practical meaning from a welder's point of view of this group of oscillograms is to show the rates of recovery of the two machines required so that if the arc is momentarily extinguished by short circuit, the moment the short circuit is removed the arc shall reestablish itself and it will not be necessary to wait for the machine to build up before obtaining the arc again.

Fig. 9B shows the current in the neutralized machine starting from open circuit, the lettering having the same meanings as before. It will be seen that the current simply rises from zero to its steady value and remains there without any surge whatever. At the same time the voltage drops to slightly less than its steady value and then recovers within two cycles or 0.033 of a second.

Fig. 9A shows the same phenomena in the second machine. In this case current rises to a value about 50 per cent higher than normal and then falls slowly to normal in about 14 cycles or 0.23 seconds. Simultaneously the voltage falls to about 1/3 normal and in about 2½ cycles reaches a value about 50 per cent higher than normal, finally dropping to normal in about the same period of 14 cycles.

The next set of oscillograms show tests on the set referred to above as the "second machine" but fitted with a transformer reactor adapted to its constants. It should be clearly understood that this machine was not designed for use with a transformer reactor and therefore although the characteristics of such an apparatus can very well be demonstrated by its means, yet if the design could have been modified in the manner described in the writer's previous paper,[*] namely by reducing the reluctance of the magnetic circuit and making the other changes referred to in Appendix I of that paper, very much superior results could have been obtained. Some of the oscillograms reproduced below seem to give characteristics of a not very favorable type but these in all probability do not characterize commercial machines fitted with a transformer reactor since in these machines the generator and transformer are especially designed to suit one another.

In the oscillograms, Fig. 10C shows the machine operated without the transformer reactor but with resistance equal to that of the transformer secondary inserted in the field in its place. It will be seen that when the current is switched on, there is a very marked rise in the first few instants, soon settling down to steady value. In this diagram the lettering is the same as that used previously. Fig. 10B shows the effect of closing the circuit when the transformer reactor is used. It will be seen that the increased value of the current which characterized Fig. 10C has now been entirely eliminated. The current now simply rises to a steady value and remains there. The lettering is the same as before save that the voltage across the secondary of the transformer has also been recorded in curve *F* zero line *G*. Under steady conditions the voltage across this secondary is simply the *IR* drop equal to about 150 volts. The most striking thing about this curve is the high peak of voltage at the moment of closing the circuit. This amounts to approximately 1,000 volts in this test. Fig. 10A shows the effect of suddenly opening the circuit with the transformer reactor in circuit. The lettering is the same as before and it is noticeable that we also get a high-voltage kick when the circuit is

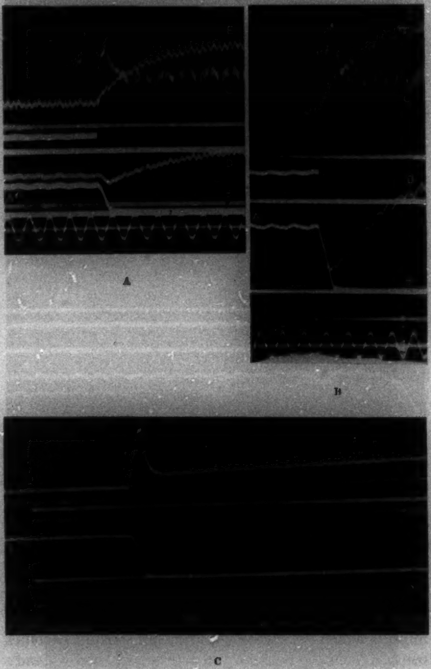


Fig. 8—Open Circuit on Two Machines

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[*] *loc cit.*

open, in this case amounting to about 1,160 volts. Referring to curves *C* and *D* which show the terminal voltage and the field current, we see that as soon as the circuit is open a considerable kick of voltage is formed by the discharge of the reactance exactly as in Fig. 10B. When the reactance is discharged, the field begins to increase in the fashion normal in any d-c machine and at the end of 23 cycles it has not yet attained a steady state. Thus these tests do not confirm the claim which is often made that the transformer reactor enables a machine to pick up more rapidly than it otherwise could. In fact this seems obvious from first principles. All a transformer can do is to supply a short period impulse which ends when the armature current becomes constant. If the field current has not reached a steady value by the time the armature current has ceased to vary, the transformer can not help it because it becomes inert as soon as the armature current becomes constant. The source of the improvement must be looked for in another direction. In Fig. 10A the field current (and hence field volts) does not drop off so much as it does in Fig. 11A (no transformer reactor) and hence the field starts to recover from a higher point. In other words since the mutual inductance is less in Fig. 10A there is less change in field current. During the above tests the armature current had the value of 75 amperes.

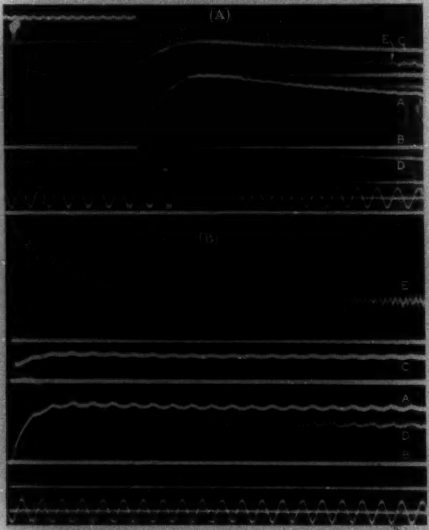

FIG. 9—CURRENT RISE ON CLOSING THE CIRCUIT ON TWO DIFFERENT MACHINES

Since a large continuous current flows through the primary circuit of the reactor transformer during its operation, it would seem at first sight that the iron must be highly saturated and it was thought desirable to study the effect of introducing a variable air gap into the magnetic circuit of the transformer. Figs. 12, 10A and 11C show corresponding oscillograms for cases where the air gap had values of zero, 1/8 in. and 1 in. respectively. Comparing these we perceive that the differences are quite slight. These show the effect of breaking the circuit. Numbers 10B and 11B correspond to 1/8 in. and 1 in. air gaps respectively and show the effect of making the circuit. These again are quite similar and it would therefore seem that an air gap in the magnetic circuit does not exert any important influence. These also show the same high voltage, that in Fig. 11C being 800 volts while in Fig. 11B the voltage is 950.

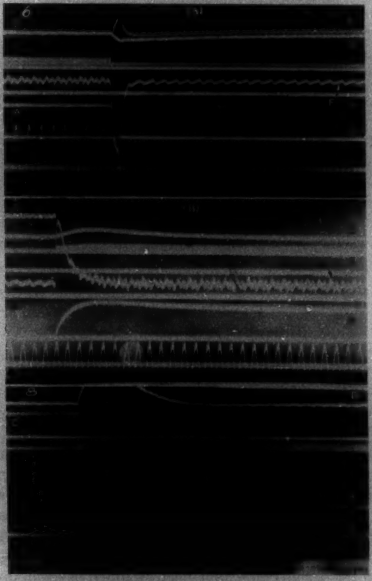

FIG. 10—CURRENT RISE ON CLOSING THE CIRCUIT WHEN TRANSFORMER REACTOR IS USED

Having determined that the length of air gap does not exert an important influence, later tests were taken with the air gap of 1/8 in. Figs. 10B and 13A show the effect of closing the circuit with currents of 75, and 156 amperes. The voltages corresponding to these tests were 850 and 2,500 respectively.

Figs. 10A and 13B show the effect of breaking circuit under similar conditions. The voltages in these cases being 850 and 2,200. As expected these voltages are roughly proportional to the current and therefore at 300 amperes one would anticipate a voltage of approximately 4,000 to 5,000 volts.* It should be repeated here that voltages as high as this are unlikely to be found in commercial machines and it would be of interest to know just what the voltages are in practical cases. It is clear that since such a high-voltage kick can only be balanced by a corresponding kick in the field circuit, these voltages must also appear across the field which would make handling the machine during operation very dangerous to life unless something were done to modify them.

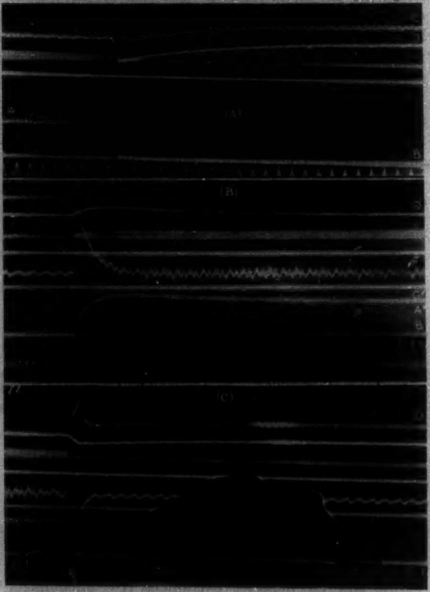

FIG. 11—OPENING THE CIRCUIT WITH TRANSFORMER REACTOR

Thus we find that somewhat similar results can be obtained, either by the use of the transformer (but at the expense of high-voltage kicks) or by the inherent design of the machine without any transformer or voltage kick. We have now to investigate how this comes about. Let us first study the closing of the circuit from an open-circuit condition. If we make a mathematical analysis such as is given in my paper mentioned previously, we find that the current immediately after the circuit is closed is made up of 3 components:

1. A steady state component.
2. The armature transient—a component containing a rapid logarithmic decrement whose rate of decrease is approximately such that the transformer volts induced by the decay of the flux interlinking the series winding and that interlinking any external reactances there may be, shall balance the rotation volts. This transient is always opposed in direction to the steady-state current. This may easily be shown by considering the case where the field current does not vary at all.

Equation (**51**)—Appendix I of the former paper is

$$\frac{n_1^2}{p}\frac{di_{33}-i_1}{dt} + Kn_1(i_{33}-i_1) - L_0\frac{di_1}{dt} = 0$$

If $i_{33}$ is constant (no mutual induction)

$$Kn_1i_{33} = K_{n1}i_1 + \left(L_0 + \frac{n_1^2}{p}\right)\frac{di_1}{dt}$$

The solution of this is if $K_{n1}L_{33} = E_1$ the rotation volts due to the field current

$$i_1 = \frac{E_1}{K_{n1}}\left(1 - e\frac{-K_{n1}t_2}{L_0 + \dfrac{n_1}{p}}\right)$$

Thus the armature transient is necessarily opposed to the steady-state current.

3. The field transient due to the variation of the current in the field. This will always be in the same direction as the steady-state current. Its rate of decrement is such that the sum of the transformer volts due to the variation of the main flux interlinking the field winding and any fluxes interlinking external reactances will balance the resistance volts (or resistance and rotational volts in the shunt type of machine). In proving that this field transient must always be in the same direction as the steady-state current, it should be pointed out that there is a slight error in Fig. 3 of my former paper, reproduced, corrected in Fig. 14. This may be taken as before to refer to a separately excited machine in which flux changes are due entirely to changes in the current in the series coil. If the series current suddenly changes from $I_a$ to $I_b$ then for the case of little or no

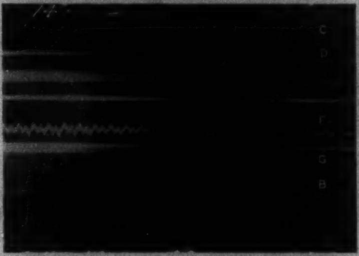

FIG. 12—OPEN CIRCUIT WITH ZERO AIRGAP IN TRANSFORMER

leakage the change in ampere turns is instantly masked by transient currents in the separately excited coil (shown at *F*) so that at the first instant there is no resultant change in flux. Since the series and separately excited coils are wound in opposition, this involves a momentary increase in the field current which is confirmed by the oscillograms of Fig. 10c for instance, or many others.

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*In all these tests the circuit was opened by opening a circuit breaker and closed by closing the same breaker by hand. The speed of opening or closing can be determined from the oscillogram.

Thus these three components are shown in Fig. 15, *A* being the armature transient, *S* the steady component and *F* the field transient, and their sum must be zero at the moment of closing the circuit. Adding them up as shown *dotted* we clearly get a curve which may have any degree of overshoot just as we find in practise. It will be clear that we can control the rates of decrement of these transients in several ways. By increasing the external inductance in the armature circuit we can slow down the armature transient as at *B* and by increasing the resistance or reducing the inductance in the field circuit we can increase the rapidity of the field transient as at *G*. Clearly if the armature transient is made slower the overshoot will be less and the same follows if the field transient is made more rapid. Figs. 13c and 13a only differ because in the former the external reactance is cut out. Yet the overshoots are 220 per cent and 140 per cent respectively.

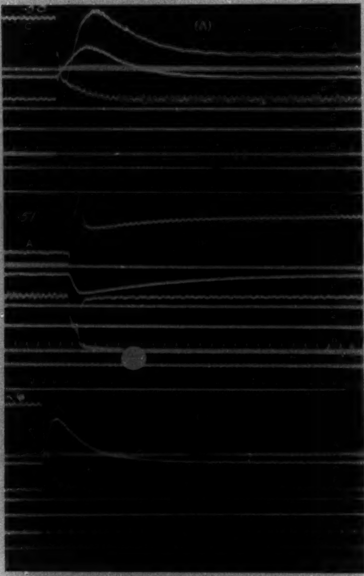

Fig. 13—Further Tests With Reactor Transformer

Clearly it is the field transient that is responsible for the overshoot since if it were zero, overshoot would be impossible, and if we can reduce or eliminate this, we shall get rid of the overshoot. The field transient, however, only exists and appears in the armature circuit in virtue of the mutual induction between the two as was shown in the short investigation just given. Consequently if we reduce the mutual induction to zero or as low as possible, we can eliminate the field transient from the armature circuit and this can be done no matter how great its magnitude.

Another plan, however, will be to design the machine so that the field transients are inherently of small magnitude and these two plans correspond to the two machines tested. These are discussed in turn.

The constants of the two machines under certain conditions are as follows:

| | Neutralized welder | Second machine |
|---|---|---|
| Rotation volts per ampere in series winding and resistance of series circuit | 0.348 | 0.70 |
| Rotation volts per ampere in shunt winding | 14.5 | 55.0 |
| Coefficient of self-induction of armature circuit (with reactor) | 003.0 | 009.0 |
| Coefficient of self-induction of field circuit | 1.26 | 27.9 |
| Resistance of field circuit | 6.4 | 260.0 |
| Coefficient of mutual induction between shunt and series | 0.08 | 0.3 |
| | | 0.0045 without reactor |

In order to form a clearer physical idea of the balance of voltages under transient conditions in these machines, we may take advantage of the fact several times pointed out theoretically and confirmed experimentally by Professor A. R. Miller that these transients may sometimes take an oscillatory form. It has long been known (see for instance Steinmetz, A-C phenomena, Appendix II) that alternating current methods of analysis (including the vector diagram and the "symbolic" method) can be applied to these currents and we shall accordingly endeavour to draw the vector diagram for this case. In the ordinary vector diagram the instantaneous values of the function are obtained by causing the vector diagram as a whole to rotate at uniform speed, the extremity of each vector tracing out a circle, and projecting each vector on a fixed axis. In the oscillatory vector diagram the extremity of each vector must trace out a logarithmic spiral and thus the diagram must be conceived as shrinking as it rotates all its component vectors however, preserving the same relative magnitudes and phases. In drawing the diagram itself the chief difference is that an inductive voltage $L \dfrac{di}{dt}$ no longer lags 90 deg behind its current but *more* than 90 deg thus representing the fact that the decrease of the flux continually yields up energy. In fact if

$$i = Ie^{jqt} \quad L\frac{di}{dt} = jLqIe^{jqt}$$

but if $i = Ie^{(-a+jq)t}$ $L\dfrac{di}{dt} = (-a + jq)\,LIe^{(-a+jq)t}$.

In developing this vector diagram it will be convenient to state the constants in a form corresponding to an equal number of turns on the series and separately excited fields. Clearly $K_{11}/K_{12}$ is the ratio of turns on these coils. Multiplying $K_{12}$ and $M$ by this ratio and $L_2$ by its square we get

| for the "second machine" | for the neutralized welder |
|---|---|
| $K_{11} = K_{12} = 0.66$ | $K_{11} = K_{12} = 0.348$ |
| $L_1 = 009$ | 003 (in example 0.00096) |
| $M = 0041$ | 0007 |
| $L_2 = 0052$ | 0007 |
| $r_2 = 05$ | 0036 (in example 0.025) |

Making use of these constants the equations read

$$(r_1 + K_{11} + L_1p)\,i_1 + (K_{11} + Mp)\,i_2 = 0 \qquad (1)$$

$$( \qquad Mp\,i_1 + (r_2 + L_2p)\,i_2 = 0 \qquad (2)$$

In these equations $p$ is to be understood not as $\dfrac{d}{dt}$ but as a complex quantity whose value may be ascertained as follows.

Let

$$i_1 = 100\,e^{(-20.3+33.25j)t} \text{ an oscillatory function}$$

$$\frac{di_1}{dt} = (-20.3 + 33.25\,j)\,i_1$$

Therefore $\qquad p = -20.3 + 33.5\,j.$

Further a plus sign has been placed before the terms containing $i_2$ since in drawing the vector diagram we wish to follow alternating-current conventions. It is usual in a 1:1 transformer to denote the resultant of primary and secondary currents by $i_1 + i_2$ notwithstanding that the currents are opposite in direction whereas in d-c practise the resultant of two opposing currents is denoted by $i_1 - i_2$. We may now readily calculate the various quantities concerned.

$$Ki_1 = 66$$

$$Mpi_1 = -8.4 + 12.6\,j$$

$$L_1pi_1 = -16.8 + 25.2\,j$$

$$r_2 = i_2p = -055 + 0.172\,j$$

$$L_2 = -88 - 25\,j$$

$$Ki_2 = -58.2 - 16.6\,j$$

$$L_1 + i_2 = 12 - 25\,j$$

$$K(i_1 + i_2) = 7.8 - 16.6\,j$$

These are shown in the accompanying diagram in which $i_1$ (half scale) is shown at $OI_1$ on the right. $L_1pi_1 = OE_{11}$ the emf of self-induction now lags *more* than 90 deg since we have an oscillating circuit. $OE_{12} = Mpi_1$ is in the same direction but of reduced length. The current $OI_2 = i_2$ must be such that its resistance $E_{21}E_{22}$ and reactance volts $OE_{21}$ sum up to a quantity equal and opposite to $Mpi_1$, *viz.*, to $OE_{22}$. Thus the second equation is satisfied. The first equation states that

$-\{K(i_1 + i_2) + Mp\,(i_1 + i_2)\} = i_1\,(r_1 + L_0p)$. Adding $OI_1$ and $OI_2$ we get $OI_0 = i_1 + i_2$. $K(i_1 + i_2)$ is shown at $OE_{13}$ and $Mp\,(i_1 + i_2)$ at $OE_{14}$. It will be seen that their sum is equal and opposite to $OE_{15} = L_0pi_1 = (L_2 - M)\,p_{21}$.

In studying this diagram it will be convenient to conceive that armature and field current each produces its own flux just as if the other were absent, these two fluxes then combining to form the resultant observable flux. In the field circuit then the voltage $Mpi$ induced by the armature current is balanced by the field impedance drop $(r_2 + L_2p)\,i_2$ in the usual manner. In the armature circuit two points of view are possible.

1. As shown more clearly in the diagram, the rotation voltage due to the resultant current $(i_1 + i_2)$ plus the inductive voltage induced in the armature by the main flux are balanced by the armature resistance drop and inductive voltage due to the leakage reactance. It is clear from this that balance can not be obtained without a considerable leakage self-induction in the armature and this explains why this is required to obtain an oscillatory solution.

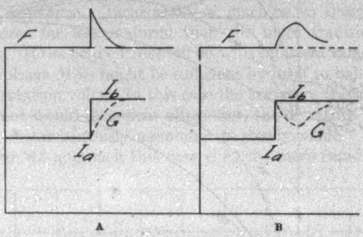

Fig. 14—Effect on Field of Sudden Change in Armature Current

2. A second point of view of course would be that all quantities proportional to armature current are balanced by all quantities proportional to field current.

In the above equations it will be noted that we have equated the transient voltages round both field and armature circuits to zero. All the external emfs are balanced by the potential drops and rotation voltages due to the steady currents and hence it follows that the sum of the transient voltages round the circuit is zero. Here of course $i_1$ and $i_2$ must be held to exclude any steady-state components. If they did not we could not of course apply the vector diagram to them.

This diagram may be regarded as a complete substitute for the treatment of the subject by differential equations which is of course extremely general but extremely cumbrous. Eliminating $i_2$ from equations (1) and (2) we get

$$(r_1 + K_{11} + L_1 p)\, i_1 - \frac{(K_{11} + Mp)\, Mp}{r_2 + L_2 p}\, i_1 = 0$$

Omitting $i_1$, rearranging the quantities according to powers of $p$ and solving the quadratic so formed we get

$$p = \frac{K_{11}M - (r_1 L_2 + L_1 r_2)}{2\,(L_1 L_2 - M^2)}$$

$$\left(1 \pm \sqrt{1 - \frac{4\,(L_1 L_2 - M^2)\,(K_{11} + r_1)\, r_2}{r_1 L_2 + l_1 r_2 - K_{11}M}}\right)$$

This is of course identical with that derived from the differential equation and so far we have nothing new. In any numerical case it perhaps provides the simplest way of calculating $p$.

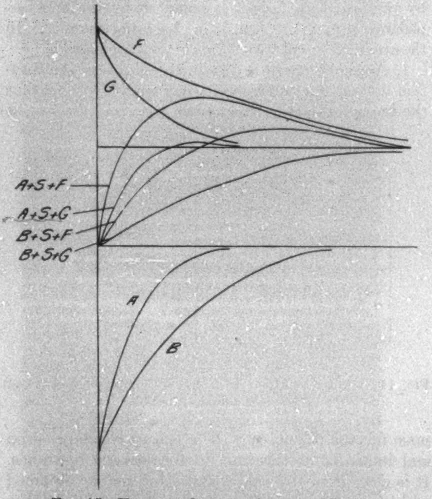

FIG. 15—HOW THE CURRENT SURGE IS MADE UP

A more geometrical method of determining $p$ is the following: In any quadratic whose solution is imaginary the usual formula

$$x = -b \pm \sqrt{b^2 - c}$$

may be written

$$x = -b \pm j\sqrt{c - b^2} = Re^{j\theta}$$

In this case

$$R^2 = b^2 + (c - b^2) = c$$

summing the squares of real and imaginary parts.

Regarded geometrically this appears as follows: In the triangle $ABC$

$$AB = \sqrt{c}$$
$$AC = -b$$
$$BC = \sqrt{c - b^2}$$
$$\tan\theta = \sqrt{c - b^2}/b.$$

Consequently $AB$ represents $p$ and knowing $c$ and $b$ it may be determined by this construction without calculation from the formula. In our case

$$c = \frac{(K_{11} + r_1)\, r_2}{L_1 L_2 - M^2} \text{ and } -b = \frac{K_{11}M - (r_1 L_2 + r_2 L_1)}{2\,(L_1 L_2 - M^2)}$$

But in place of determining the arbitrary constants either by simultaneous equations or by the Heaviside expansion theorem we have a much simpler process. Suppose the terminal conditions are:

When $t = 0$ $i_1 = a$ units (say − 75 amps for instance)
$i_2 = b$ units (say zero for instance)

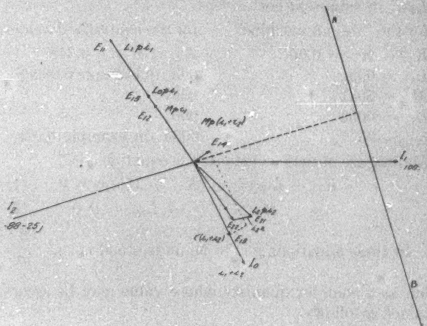

FIG. 16—OSCILLATORY VECTOR DIAGRAM FOR WELDER TRANSIENTS

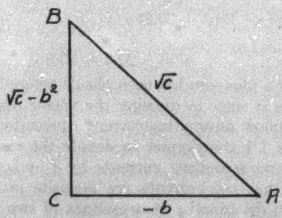

FIG. 17—GRAPHIC SOLUTION OF QUADRATIC IN "p"

To satisfy these conditions we have merely to choose our axis of projection (in the case where $i_2$ is zero when $t = 0$) so as to be perpendicular to $i_2$ on the diagram as at $AB$ and our scale so that the projection of $OI_1$ on $AB$ is 75 units. Clearly we can find an axis of projection such that the projections of $OI_1$ and $OI_1$ on it bear any ratio whatever to suit any desired terminal conditions, and a scale to suit any case we desire to study. The vector method therefore is a complete substitute for the method of differential equations in the study of oscillatory transients not only in this but in all other cases (not involving equations of higher than the second order) in which they occur.*

In endeavouring to discuss the case of "real roots" we must return to direct-current conventions if our results are to have the accustomed form. Thus the equations will be

$$(r_1 + K_{11} + L_1p)\, i_1 - (K_{11} + Mp)\, i_2 = 0$$
$$Mpi_1 - (r_2 + L_2p)\, i_2 \quad = 0$$

Now it is clear that when the vector representing an inductive voltage lags 180 deg behind its current the oscillatory solution becomes exponential and the above diagram encourages us to try and form an equivalent for the exponential case.

Let

$$i_1 = 639\epsilon^{-50.4t} \quad - 715\epsilon^{-103t}$$
$$i_2 = 630\epsilon^{-50.4t} \quad - 630\epsilon^{-103t}$$

When $t = 0$

$$L_1 \quad = -76 \qquad Mpi_1 = 168$$
$$L_2 \quad = 0 \qquad L_2pi_2 = +168$$
$$K_{11}L_1 = -50 \qquad Mpi_2 = +133$$
$$L_1pi_1 = 185$$

Since $i_2 = 0$, $i_2r$ and $K_{11}i_2$ are both zero which simplifies the equations. This leaves only three terms in the armature equation

$$K_{11}L_1 + L_1pL_1 - Mpi_2$$
$$-50 + 185 - 133 = 0$$

The diagram which of course is a straight line shows that $Mpi_2$ is in the same direction as $K_{11}i_1$. Since it has to be balanced by $L_1pi_1$ unless $L_1$ is very great this will demand very rapid change in $i_1$. If we reduce either $M$ the mutual induction or $pi_2$ the rate of change of $i_2$ then $L_1pi_1$ need not be so great and $i_1$ may vary more slowly.

Now take a case where the slope of the field current is negative

Let

$$i_1 = -79\epsilon^{-154t} \quad + 28\epsilon^{-50.4t}$$
$$i_2 = 100\epsilon^{-154t} \quad - 100\epsilon^{-50.4t} -$$
$$pi_2 = -15{,}400\epsilon^{-154t} \quad + 5{,}040\epsilon^{-50.4t}$$

When $t = 0$

$$i_1 \quad = -51 \qquad L_1pi_1 = 10.35$$
$$i_2 \quad = 0 \qquad Mpi_1 = 7.5$$
$$K_{11}L_1 = -17.6 \qquad L_2pi_2 = -7.22$$
$$Mpi_2 = -7.22$$

For the same reasons as in the last paragraph the equation for the armature circuit reduces to

$$K_{11}L_1 \; + L_1pL_1 - MpL_2 = 0$$
$$-17.6 + 10.35 + 7.22 \quad = 0$$

Thus in this case $Mpi_2$ the voltage due to the decrement of the flux due to the field alone aids that due to the decrement of the armature flux to balance the rotation volts. If therefore a fairly large external reactance is employed the rate of decrement of the fluxes may be made relatively small and if the machine is designed with low values of $L_1$ and $M$ all the transient voltages in the machine itself may be kept very small, the external reactance setting the pace of current changes and the machine following as rapidly as if it contained nothing but resistance. Incidentally a machine so designed requires far less material than the more traditional type. If the field current fell off with sufficient rapidity its voltage $Mpi_2$ might be sufficient by itself to balance the rotation volts. In this case the armature transient current would disappear altogether, the armature current instantaneously assuming its steady value. The nearer we approach this case *i. e.*, the more rapid the decrease of the field current, the smaller will be the armature transients, and the more rapid the rise of the current (without overshoot) to its final value.

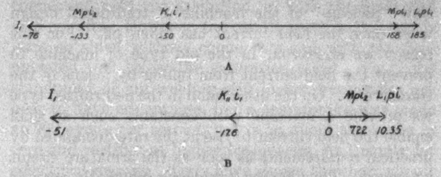

FIG. 18—NON-OSCILLATORY DIAGRAMS FOR WELDER TRANSIENTS

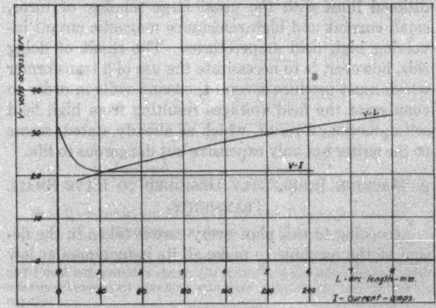

FIG. 19—ARC VOLTAGE PLOTTED AGAINST CURRENT

Thus we see that if the field current *rises* when the armature circuit is closed the inductive voltage from the field circuit aids the rotation volts in the armature and a very rapid rate of variation of armature current (with consequent overshoot) is necessary to balance them. Overshoot is essentially due to the field current rising. If we make arrangements for the field current to *fall* as in the neutralized machine tested the field inductive voltage will help to balance the rotation volts, and no very great rate of variation of armature current is necessary with consequently no overshoot. This is amply confirmed by the oscillograms.

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*For the actual plotting of the transient it is probably most convenient to derive the solution from the diagram and plot it as if there were no decrement. Then multiply the ordinates by $\epsilon^{-at}$ remembering that this is unity when $t = 0$.

But the machine, to be practical, must have quick recovery as well as absence of overshoot. The cause of slow recovery as we have seen was the drop in field current after the armature circuit is opened and the slow "pick-up" of the machine of traditional design when once the field current has fallen off. For this reason we endeavour in the old type of machine to prevent the field current from falling by means of the transformer. On the other hand in the neutralized type we provide a machine with constants such as shall enable the field current to rise at the rate demanded by practical requirements as soon as the armature circuit is opened. Thus having a machine inherently capable of quick recovery we need not be afraid of the field current falling off and can use reduction of the field current as a means of preventing overshoot.

Finally to sum up there are essentially two methods of eliminating transients.

### TRADITIONAL DESIGN WITH CORRECTING TRANSFORMER

According to this plan, the design of the field circuit is not of very great importance since whatever happens it can always be set right by an adequate transformer. It is possible therefore to continue to design it on traditional lines with the usual large number of turns, small current and high reluctance magnetic circuit involving high field ampereturns. The result of doing this, however, is to necessitate the use of a transformer which must produce several thousand volts in order to counteract the field voltages resulting from high field self-induction, a result, which as already stated, seems to the writer not only expensive but dangerous to life.

### A MACHINE INHERENTLY DESIGNED TO HAVE SMALL TRANSIENTS

According to this plan every care is taken in the design of the machine to make all its inductances as low as possible, especially that of the field. In order to do this, special pains are taken to minimize the reluctance of the magnetic circuit thereby permitting a small number of turns on the field.

Since although these inductances are small thay can create fairly high voltages if the current varies very rapidly, it is desirable even in such a machine to slow down the armature transient by means of heavy external self-induction. Thus we have a design whose operation may perhaps be better understood if we use the old term for self-induction and call it a machine of small electrical inertia combined with a large external inductance which provides the main electrical inertia of the system.

Of course there is a third plan which consists in combining plans 1 and 2, namely partially redesigning the field so as to reduce the self-induction by reducing the reluctance and number of turns while still employing a transformer to neutralize the mutual inductance between field and armature. This is probably the plan adopted in commercial apparatus containing the so-called transformer reactors, but it seems difficult to understand why, if the field design is to be modified at all, it is not better to go the whole way and design it so as not to need a transformer instead of only half-way when we still need a transformer.

In conclusion it is desirable to say something in justification of another point in the investigation. In my former paper "The Neutralized Welder," the arc was replaced by a constant voltage in formulating the differential equations. This procedure has been criticized in certain quarters but may be justified from Fig. 19 which shows arc voltage as a function of current and as a function of arc length. From this it will be seen that the voltage across the arc is almost exactly constant and independent of the current for the entire welding range of currents.

### ACKNOWLEDGMENT

The author is indebted for Fig. 19 to Messrs. E. C. Easton and F. B. Lucas to whom as well as to Professor A. R. Miller he wishes to extend his acknowledgment for assistance in the preparation of this paper.

# High-Frequency Arc Welding Generator

BY G. A. JOHNSTONE*
Member, A.I.E.E.

***Synopsis.**—Extensive tests have demonstrated important advantages favoring the use of high frequency current for electric arc welding and have led to the development of a 900-cycle double induction generator of attractive characteristics and capable of supplying several different arcs at once. Some test results and a description of the high frequency generator are given.*

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EXPERIMENTS with induction generators operating at frequencies ranging from 500 to 9,000 cycles per second, have shown that currents of such relatively high frequencies have important advantages for use in metal arc welding and for other arc applications of heat. Experience with the inductor machines has shown them to have inherent characteristics that make them suitable for supplying current to electric arcs, and to give them both construction and operating advantages over d-c welding generators.

FIG. 1—A MULTIPLE-CIRCUIT 900-CYCLE 3,600-RPM, DOUBLE-CORE SINGLE-FIELD ARC WELDING GENERATOR

The generator as now commercially developed is of the double core type (see Fig. 1) designed to operate at 3,600 rpm to produce welding currents at a frequency of 900 cycles per second. The machine has the simplicity and the ruggedness of a squirrel cage motor, although the length of the air gap is almost twice that usually employed in an induction motor. The rotor teeth or poles are laminated, and the direction of rotation, of course, is optional. The relatively high speed enables direct connection to gasoline engines of similar speeds, resulting in portable sets, compact and light in weight.

The generator is self-excited, as indicated in Fig. 2, through a bridge connected full-wave rectifier. This generator circuit occupies 3 of the 60 stator teeth; the d-c field circuit is a single coil. The high reactance of the field coil at 900 cycles aids the operation of the rectifier and permits the use of the smallest number of units in series for the voltage needed. The higher frequency also lends itself to the use of condensers in connection with the excitation, in both the fields and load circuits. However, the results given in this article were obtained without condensers and with the field operated well below the saturation point. From the standpoint of arc welding still higher frequencies appear to have advantages, but a compromise was made at 900 cycles per second, partly to avoid the losses in core and rectifier at higher frequencies, and partly for structural reasons. Tests have shown the short circuit losses to check, or nearly equal, the total load copper losses plus the no load losses. Iron losses at higher frequencies also influenced the decision upon 900 cycles per second as the best operating frequency. As now designed, the generator efficiency is 80 per cent or higher for 200-amp and larger sizes. A 7½-hp motor is used for the 200-amp size, 10-hp for the 300-amp size.

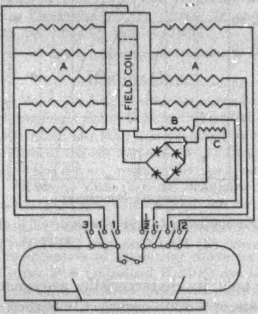

FIG. 2—SCHEMATIC DIAGRAM OF THE WINDINGS OF THE GENERATOR SHOWN IN FIG. 1

The 2 stator windings are divided into 10 welding circuits (*A* and *B*) and 1 field self-excitation circuit (*C*) involving a full-wave rectifier. Circuits may be switched according to number of circuits and welding current required

The multiplicity of welding circuits is noteworthy. By proper switching arrangement there may be as many operators as there are circuits (each circuit is independent; individual coils embrace only one pole, and there is but one coil per pole), or the circuits may be combined to give greater current capacity to fewer operators. The connection scheme shown in Fig. 2

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*Great Lakes Elec. Mfg. Co., Chicago, Ill.

*Presented at the A.I.E.E. Winter Convention, New York, N. Y., Jan. 23-27, 1933.*

would serve one operator with 2 arcs, or 2 operators each with 1 arc.

Volt-ampere curves for single circuits of this generator are shown in Fig. 3, where the dotted curves show values obtainable by field adjustment; however, as pointed out later, a field rheostat generally is unnecessary. As all the circuits have like characteristics and none is affected by the current in any other, the shape of the volt-ampere curve will be the same for all values of current obtained when several circuits are connected in multiple. For example, one main circuit may give 27½ amp short circuited, 26 amp at 25 volts, and 85 volts on open circuit; then if 8 main circuits are used in multiple the short circuit current will be 8 × 27½ = 220 amp, the load current 208 amp at 25 volts, and the open circuit voltage 85. This holds for any number of circuits.

The half circuit, it may be explained, uses half as many poles as a main circuit and has twice the number of turns per pole; its characteristics are exactly proportional to those of a main circuit. It is used to provide a smaller step in adjusting welding current to the value desired for any given work. The generator is flexible in this respect. It may be seen that, by simple changes in the switching, several circuits can be used in series for higher open circuit voltages, or separate combinations of circuits can have different voltages if not used in multiple. The characteristics of all such circuits will be similar and the short circuit ampere turns per pole for all will be the same for any given field strength.

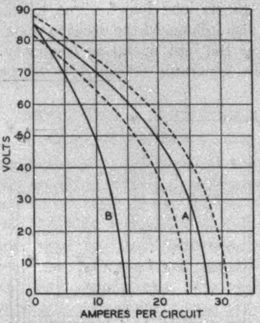

Fig. 3—Characteristics of 200-Amp 900-Cycle Arc Welding Generator: (*A*) Full Circuits, (*B*) Half Circuit

These characteristics are entirely inherent in the generator; no external reactance or resistance is used. A set without field rheostat, even without instruments, is entirely practical from an operating standpoint. The switches afford all the control necessary and, being plainly marked either in amperes or units, indicate almost exactly the value of the current available for a certain setting.

In connection with the voltage regulation and the interrelation of circuits it is worth while to note that, although the statement that all circuits are independent of each other is true for all practical purposes, there is a small compounding effect. If, say, all but one of these circuits are shorted, the voltage on the open circuit will have a permanent rise of about 2 per cent with a 2 per cent drop in speed when the generator is self-excited; the field ammeter will show a corresponding permanent increase in field current. When the generator is separately excited, as it may be from any constant potential d-c source, the field ammeter will show a small upward kick of about the same magnitude as the permanent rise when self-excited, not more than 5 per cent of the maximum throw of the needle. This slight compounding effect is the only evidence of any inter-relation of the various circuits. When the machine is self-excited, the field current at open and short circuit is as shown in Fig. 4.

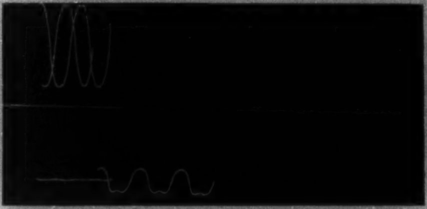

Fig. 4—Line Voltage and Field Current of 900-Cycle Welding Generator Self-Excited Through Rectifier; (Left) Open Circuit; (Right) Short Circuit (Partially Retouched)

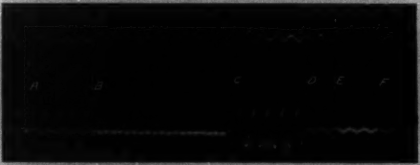

Fig. 5—Voltage (Upper) and Current (Lower) Characteristics of 900-Cycle Welding Generator Arising from Make and Break of Short Circuits

Momentary breaks at *A* and *C*; longer breaks at *B*, *D*, and *E*; make (circuit closed) at *F*

Fig. 5 shows that there are no surges of more than 10 per cent above normal in either voltage or current when short circuits were made and broken by wiping the welder's rod-holder quickly across the edge of the grounding base. It may be seen that the voltage and current curves show practically normal conditions immediately after the short circuit is broken or made.

Fig. 6 shows the voltage and current conditions while welding with a current of about 180 amp. These curves were taken with the same setting of the oscillograph as those in Fig. 5, and the same circuits of the generator were used for welding as were shorted in Fig. 5. The voltage curves of Figs. 5 and 6 were on a scale of 10 volts per mm. The open circuit voltage (Fig. 5 upper curve) has a value of approximately 100 volts maximum and the welding voltage (Fig. 6 upper curve) has a value of 43 volts maximum. These would be respectively 71 and 30 effective, assuming sine waves.

Fig. 6—Relations of Arc Voltage (Upper) and Current (Lower) for 900-Cycle 200-Amp Arc Welding Generator

Note the effects of short-circuiting the arc (toward the right)

In Fig. 6 is shown a short circuit of the arc that lasted for 2½ cycles or about 1/360 sec, corresponding in time to 1/6 cycle of 60-cycle current. The current curve shows a slight increase during the short circuit and a noticeable change of shape, the front of the current wave during steady arc conditions being peaked, but during the short circuit the 5 crests have their peak at the tail of the wave. By the flattened crests of the current waves the short circuit is predicted a few cycles ahead of its actual occurrence. The zero points of the waves show no shift.

The machine described makes a practical welding generator, with which metal arcs are easy to strike and hold, and good penetration is obtained. It is particularly good where the new heavy coated rods are used and in other work where reversed polarity of direct current is recommended. With a carbon torch this high frequency current also is useful. The arc projects so well away from the carbons that it is almost as handy to apply to the work as is a gas flame. In the case of the carbon arcs the no load voltage used is the same as for metal arcs. The carbon arcs operate at from 45 to 50 volts, with correspondingly lower current per circuit. It should be noted that this generator is operated at low open circuit voltage; comparable to d-c machines in this respect. Metal arcs are easy to strike and hold at from 65 to 70 volts. Arcs of smallest current values can be held successfully with open circuit voltages below 100.

Among the features of this high frequency generator that command attention are:

1. Multiple circuits for more than one operator; simple adjustment of circuits.
2. No transients that affect the welding operation.
3. Low open circuit voltage.
4. Inherent regulation, no external reactance or resistance required.
5. High efficiency.
6. Self-excitation, or optional separate excitation from any d-c source.
7. Weight and cost low; less than ½ the usual d-c machine; comparable to 60-cycle transformer equipments.
8. Three-phase loading of power lines as compared to single phase 60-cycle transformer sets.
9. Rugged construction of rotor; no windings; no commutator; no brush wear.
10. Optional direction of rotation.

## Bibliography

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## Discussion

**F. Creedy:** Some years ago the writer carried out some work with the high frequency arc in Europe. The frequency used was only about 300, much less than that proposed by Mr. Johnstone but the operation of the arc was remarkably steady, just about equal to that of the d-c arc produced by the type of arc welder then in use. Of course since then the steadiness of the d-c machine has been a good deal increased. I can therefore confirm all that Mr. Johnstone says as to the advantages of high frequency for a-c welding.

A simple modification of the binary converter (described in the writer's paper *The Neutralized Welder*[1]) can be made which enables it to take three-phase, 50- or 60-cycle current at the stator terminals and deliver single-phase 300-360-cycle current at a couple of slip rings. All this may be done with a single machine having only one winding and not two on either member. Constructionally it is exactly like an ordinary induction motor and can use the same parts and only requires special punchings. It operates on 60 cycles at 3,600.

Regarding the subject broadly, an objection often made to these high frequency machines is that if we have to have rotating machinery anyhow we might as well use direct current. Which will win in the end is a matter of commercial competition.

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[1] A.I.E.E. Trans. Vol. 50, 1931, p. 662.

# Communication Requirements of Railroads

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and

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*Synopsis.—Large railroad systems are complex organizations requiring extensive communication services to handle their special operating problems and to enable them adequately to reach and serve the public. Brief descriptions of the major requirements for circuits, switchboards, radio, carrier, plant and apparatus are given.*

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It is the purpose of this paper to outline briefly the communication requirements of a typical large American steam railroad system.

Due to limitations of space, statements will be made which apply more or less generally but are subject to detailed variations and exceptions.

A modern railroad system is a vast and complex business with tens of thousands of employees and thousands of miles of far flung lines spanning one-half and more of our continent. To function efficiently such a large business must be highly organized with a resulting division of labor into allied groups. Whether the organization be along military or departmental lines, there have been evolved departments which are generally similar on practically all roads, as indicated in the following list:

- Executive
- Transportation
- Traffic
- Engineering
- Motive Power
- Car
- Accounting
- Legal
- Treasury
- Purchase and Stores
- Real Estate and Tax
- Signal
- Electrical
- Claim
- Telephone and Telegraph
- Police
- Safety

From the above it may be presumed that there are many contacts between the railroad and the public it serves, as well as between departments, necessitating comprehensive and continuous communication service.

## TELEPHONE AND TELEGRAPH SERVICES

*Dispatching.* A regular train is one authorized by time table schedule which means that its leaving time and passing time at each station is shown in its schedule and that the train shall not pass any designated station before the designated time. If it is desired to run a train ahead of time, it is run as an extra or on the schedule of a preceding train. If no other trains were operated than those shown in the time table and if these were always on time, a railroad could be run by the time table. However, there are many extra trains operated that are not scheduled and the scheduled trains will, at times, run late due to various causes. It is therefore necessary to have other means than the time table to insure the prompt, safe movement of trains. This need has brought into being a very highly developed technique of train direction known as dispatching.

The passage of each train by a station is reported to a dispatcher located at division headquarters. It is the duty of the dispatcher to arrange for the movement of the trains around and past each other. To do this, he requires dispatching circuits, either telephone or telegraph or both. These circuits are connected into each station in his territory. If a circuit is operated telegraphically, calling of the stations is by Morse code. If the circuit is operated telephonically, calling is by means of a key which sends out coded impulses which operate a device known as a selector at the station called. The operation of the selector rings a bell and sends a tone back to the dispatcher, indicating that the bell has rung. Each station is provided with suitable telephone equipment to answer calls. Such equipment is standard, but of a more or less special type developed for the use of this service.

The dispatcher is provided with a loud speaker that is always connected to the dispatching circuit and if any station desires to talk with him, the station operator simply connects his telephone to the line and proceeds to talk. In very congested territories where many trains are involved, it is desirable also to provide the stations with loud speakers. In this case the dispatcher is saved the time of calling, as he merely announces the name or call of the station desired and proceeds with the message. Dispatching circuits vary in length from 15 mile terminal circuits to about 600 or 700 miles depending on the density of traffic. They probably average 200 miles. The number of stations connected thereto also varies widely from perhaps 15 to more than 100 with an average between 40 and 50.

Dispatching circuits are the most important on the railroad. The use of the telephone is considered preferable to the telegraph and each year sees an increase in the former at the expense of the latter. At the present time, nearly all main line and a majority of all mileage is dispatched by telephone. The circuits are usually composed of No. 9 AWG copper, although in some cases where territories are long or weather conditions severe, No. 6 AWG copper is used. These circuits are normally designed with a transmission equivalent of not over 20 decibels with a maximum of 25 decibels to the dispatcher. Often the dispatcher is located at some point other than the terminal, in which case the overall equivalent may be as large as 30 decibels.

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

*Block and Siding Communication.* To increase safety of operation, separation between trains in distance is maintained. This is done by dividing the track in sections called blocks averaging 8 to 10 miles long. Under one system known as the "absolute" but one train is permitted in any one block at a given time; under a more generally used system known as the "absolute—permissive" not more than one passenger train may occupy a block at any one time, but a freight train is permitted to follow another freight train into a block, first being warned by signal or special instruction that the block is occupied and to proceed with caution prepared to stop. The signalman at the end of each block keeps a record of all train movements in and out of the block on either side of his station. Upon the approach of a train he consults his record and if the block is clear, communicates with the station in advance. If the advance station finds the block clear he displays a stop signal against opposing trains and advises the first station that the block is clear.

The circuits used to communicate between the two stations may be either telegraph or telephone. Usually only the two stations concerned are connected to the circuit. If it is a telephone circuit, it is simplexed and the derived telegraph circuit is used as a way station telegraph circuit. As block circuits are usually short, transmission considerations do not normally govern the choice of wire, which may be either No. 8 BWG iron or No. 9 AWG copper, depending upon which is considered the more economical. If simplexed, copper is generally preferable. The block circuit which is so intimately connected with train operation is one of the more important circuits required by the railroad.

In automatic signal territory, especially with multiple tracks, manual blocking is not required except when trains are operated against traffic.

When a train takes a siding, the conductor must report to the block operator that the train is clear of the main track so that other trains may be advanced through the block without delay. Telephone circuits known as siding lines are often strung to the switch at the end of a siding to permit the conductor to call in and clear the train without his having to walk back the full length of the train, which would require considerable time in the case of a long freight train. These lines are also used before the train leaves the siding, the conductor calling up the block operator and obtaining the necessary permission to enter the block. The telephone instrument is housed in a small box mounted on a pole or in a booth. At times the siding lines are not provided and the telephone is connected directly to either the block or dispatching line.

*Telegraph Way Circuits and Telephone Message Circuits.* Where dispatching is by telegraph a second telegraph circuit, cut into the same stations as the dispatching circuit and often into additional stations, is required for handling the general divisional business and as an auxiliary circuit for the dispatcher.

Where dispatching is by telephone and an auxiliary telephone message circuit has not been provided, a telegraph way wire similar to the one described in the preceding paragraph and for the same purposes is generally available. Where a block circuit is used, this way wire is obtained from the simplex on the block telephone wires; otherwise, it is the ordinary way station telegraph wire.

Where traffic conditions warrant, a message telephone circuit is provided. This is like the dispatchers circuit in its physical makeup, except that it usually has drops to freight houses, depots and other places not connected to the dispatcher's circuit. Generally it is terminated in P.B.X.'s at each end, and the latter do the ringing. Its selectors are set with the same codes as the dispatchers circuit so that in case the latter fails, sections of the message circuit may be used to make the dispatching circuit good or the entire circuit may be turned over to the dispatcher. The way telegraph or message circuits are normally required in the transaction of local business of the division. The car distributor uses it extensively and traffic matters concerning rates, routings, reservations, etc., are handled with the division traffic agents. The division engineer uses it as a prompt means of conferring with and issuing instructions to his section and bridge foremen when necessary. In addition, many telegrams on various matters pass over this circuit. On very busy divisions, two such circuits may be required, due to the heavy volume of message traffic.

*Long Distance Telephone Service.* Various divisions are grouped under an operating head known as a general manager or general superintendent. Long distance telephone service connecting these division offices with general headquarters is obtained by the use of a phantom on the dispatching and message circuits where the divisions under control radiate from the operating headquarters. Otherwise, additional circuits are constructed or telephone repeaters provided for existing derived circuits.

Service from the executive general headquarters to general operating and traffic officers is provided by means of trunks between strategic telephone switching points.

Telephone repeaters, and entrance cable loading may be necessary to give satisfactory over-all transmission. As terminal losses on calls to local points, city ticket offices, etc., will usually equal or exceed 5 decibels, the trunk equivalent between any two points should not exceed 20 decibels.

*Private Branch Exchanges.* At a large terminal or general headquarters, there may be hundreds of commercial telephones serving the various railroad offices. These offices have numerous contacts with each other and the public. To provide the usual direct business telephone would require a huge directory listing in the telephone company's directory and place on the public the burden of searching for the particular party desired who in many cases is not known. The arrangement, as a matter of fact, would be impracticable. The need for convenient and economical distribution of such calls with a minimum of inconvenience to the public, has been met by the installation of private branch exchange switchboards. A private branch exchange switchboard is usually located in one of the railroad buildings near the center of the telephones connected to it. The local calls from one department to another are, of course, routed through this board. Sufficient central office trunks are provided to handle the traffic to and from the public. The board is manned by trained operators, on the railroad's payroll, who are familiar with the practises of the various departments served and can properly distribute the calls to the persons desired.

The private branch exchange is also used to connect the railroad's long distance telephone lines with the local terminals.

Switchboards may be either owned by the railroad or rented from the commercial companies. In the latter case connections may be established between the long distance lines and the plant of the telephone company. The P.B.X. may be either manual or semi-automatic. Semi-automatic operation usually provides for incoming city and long distance manual service and automatic or dial outgoing city and station to station service.

In some cases, it is preferable to install more than one P.B.X. within the terminal territory to take care of specialized traffic or in situations where telephones are so scattered as to make the provision of direct lines too expensive. Generally the larger city ticket offices and freight terminals are provided with P.B.X.'s of their own and are so listed in the directory. These might be handled from a central board, but in practise it is found that since the traffic is of a specialized nature and almost exclusively with the public, that greater efficiency can be obtained from a separate board. This applies only to the larger locations. At smaller places a single central board is usually better.

In executive offices where a special secretarial service is desired, small auxiliary boards connected by tie lines to the main P.B.X. are frequently an advantage.

An outlying yard several miles from the central board is a good example of specialized service requirements. The traffic in this case is largely local station to station and of a more or less special kind. To provide direct lines from the main board would often involve an expensive underground and aerial cable, whereas the separate board would be less costly.

*Pullman Reservation and Information Bureaus.* These two services require special communication arrangements.

At the Pullman reservation bureau, each car has associated with it a diagram card, upon which is indicated the space available in the car. The current month diagrams, one for each car and for each day of the month, are grouped by trains in a rack mounted on a table. The rack is built as high as a person can conveniently reach from a sitting position and of such length as to accommodate the necessary number of cars. Along the table on each side are seated from possibly 4 or 5 to as many as 40 diagram clerks, depending upon the number of sleeping car lines operating through the terminal. Each clerk has a telephone and by means of keys can connect it to any one of a number of lines appearing in the table shelf in front of the clerk. Associated with the table is an automatic telephone exchange from which extend lines to the ticket sellers in the depots, city ticket offices and hotel ticket offices. A patron desiring a section between two points on the railroad makes his wishes known to the ticket seller, who, by means of his telephone, dials the particular section of the diagram rack in which he knows the diagrams for the particular train are located. A signal lamp will light in front of several clerks facing these diagrams, one of whom will answer and give the desired space. It is to be noted that no public telephones are connected to this unit, nor does the public have direct access to it.

In addition to the above unit, another somewhat similar unit is sometimes provided known as the public reservation. The public reservation is provided with direct trunks from the telephone company's central office and listed separately under the trunk number in the directory. Incoming calls may be distributed by means of a P.B.X. to the clerks, or the lines may be multipled through the table with lamp signals in front of all or groups of operators so that if one is busy, others may answer. Pullman space reservations requested by patrons over the telephone are made at this unit. The clerk answering a call would either leave the table, go to the diagram rack and secure the space, or transfer his telephone to a line connected to the automatic unit serving the diagram board, dial the particular section desired and secure the space from the diagram clerk, then inform the patron.

The information bureau is provided with trunks from the telephone company's central office and given a separate listing in the directory. The incoming calls may be received at a switchboard and distributed to the information clerks or the lines may be multiplied through the table with answering lamps appearing in all or any number of positions. Tie lines are provided to the diagram unit so that the information clerks may secure Pullman reservations direct when asked for in addition to train information.

Some railroads consolidate the diagram and public reservation units, others combine the public reservation and information bureaus and some feel that separate units are more desirable. Generally it is believed that a separate diagram unit and a consolidated public reservation-information unit is preferable.

*Centralized Reconsigning and Tracing Bureaus.* Railroad service has become so reliable that merchants have in many cases reduced stock to a very small percentage of that formerly carried depending on scheduled delivery of orders on time. This has naturally resulted in a much increased concern as to the freight movement, some shippers requesting information as to exact time their cars leave terminals and pass intermediate points enroute. This has resulted in a considerable increase in car tracing. The greatly increased movement of perishable freight has also resulted in a large increase in reconsignments or diversions. Entire train loads of fruit, for example, may be started and consigned to some point. The shippers then proceed to dispose of the freight while in transit and in a short time the railroad will receive telegrams reconsigning or diverting the cars in the train.

Modern trend is toward a centralization of tracing and reconsigning activities into central points either for the system or by regions embracing fairly large portions say one-fourth of the system mileage that is closely allied.

When through freight trains leave their initial terminals, the number, consignee or contents and destination of each car, the time of leaving, the time it passes each important terminal, and the time it reaches its destination or is transferred to another railroad is telephoned or telegraphed to the central trace bureau. At this point the cars are booked by a number system so that they can be readily located. All requests for tracing or orders for reconsignment are directed to the bureau, the latter from its records can usually answer any tracing request at once and, knowing the location of cars in transit, effect a reconsignment or diversion with a minimum of delay.

Practises vary as to the number of trains handled through trace bureaus, some railroads booking practically all through freight trains while others book only the higher class trains moving perishable freight.

In a regional plan existing telephone and telegraph facilities can usually handle the transmission of the necessary information through the regular channels. Frequently idle telephone circuits can be utilized during the night.

In a central system plan special telegraph circuits equipped with printers will usually be provided. Generally the demand will exceed existing available facilities necessitating the construction of additional lines at considerable expense.

*Morse Telegraph Circuits.* In addition to the way or message telegraph circuits previously mentioned, a network of through telegraph circuits is required. Upon these are handled a great variety of messages, daily situation reports, Pullman reservations, car tracers, reconsignments and diversions, car home routes, special passenger equipment movements and many miscellaneous messages of a general nature. The number of such messages on a large system will average from 12,000,000 to 36,000,000 or more per year.

In addition to the way wires and depending upon the particular type of organization, other circuits may be set up between the division headquarters and the general superintendent's headquarters, between the latter and important outlying terminals and general operating headquarters. General operating headquarters if more than one will usually have direct service with each other, also to the executive headquarters.

Many of these circuits are derived from simplexing or compositing telephone circuits; others are strung as single wires.

When hand sending is employed they may be operated single where transmission is one way at a time; duplex where two messages are sent simultaneously, one in each direction, or quadruplex where four messages are sent simultaneously, two in each direction. Comparatively few of these circuits are operated either single or quadruplex, the great majority being operated duplex.

When the traffic becomes sufficiently heavy to warrant their use, printing telegraph machines are used. As in the case of hand sending they may be operated single (it is called in this case simplex), duplex or multiplex. In the latter case, as many as four messages can be sent in each direction at a time. The printer sending operator types the message on a key board similar to that of an ordinary typewriter and the message is automatically typed at the other end by the receiving machine.

In the longer circuits telegraph repeaters appropriate to the type of circuit are required at intervals varying with the weather conditions and resistance of the wire from 150 to 300 miles.

In the larger terminal telegraph offices, belt conveyors along the operating tables for collecting incoming messages are desirable as they speed up the movement of messages and usually effect savings in messenger expense. Where these larger offices serve general office buildings, a pneumatic tube delivery and pick up service is desirable. Where tubes are installed the conveyor belt should be arranged, if practicable, to deposit the messages at the tube center so that they can be immediately dispatched. Tube systems are also very efficient for the handling of inter-office mail in the building.

*Local Printer and Announcing Circuits.* In addition to their use in general telegraph message service, printers are required in a number of local and short wire services.

In the new type car retarder yards as soon as a train pulls in the receiving yard the waybills are sent to the yard office usually by pneumatic tube. The yard clerks immediately start preparing a switching list indicating the manner in which the train will be switched to the classification yard. They do this on printers which simultaneously type the list in the switching towers. As the train is slowly pushed over the hump the tower operators divert the cars into the various tracks of the classification yard in accordance with the list. By the use of the printers, switching can start almost immediately, otherwise it would be necessary to wait until the list has been completed and copies sent to the towers.

A loud speaking telephone system is also provided between the yard office, hump and switch towers. This is required to provide a means of instantaneous intercommunication so that corrections and changes can be quickly made and emergency information passed between offices relative to the handling and disposition of the cars.

Ready use is found for printers at terminals for the transmission of various sorts of information such as orders to coach yards concerning the arrangement, make up and changing of passenger equipment, the arrival of freight to downtown offices, etc.

At large passenger stations, arrival of incoming trains is reported from outlying towers to the incoming bulletin board, information bureau, mail room, station master, baggage room, telegraph office, taxi cab headquarters, etc. This is done either by printers or telautograph.

In connection with or in addition to this circuit there is provided in some instances a loud speaking or public address system to announce to the waiting public the arrival and departure of trains. In lieu thereof the information is sometimes thrown on a screen by means of a projection machine.

*Time Service.* It is essential that accurate time be maintained on a railroad. At dispatcher's offices, yards and terminals accurate clocks are provided known as standard clocks with which trainmen compare their watches before starting on their tours of duty. Each day at noon eastern standard time, usually through arrangement with a commercial telegraph company, U. S. Naval Observatory time is sent over the telephone and telegraph networks of railroads to all stations. Formerly this was sent exclusively by telegraph, but at present both telephone and telegraph are used. The standard clocks are compared with the time signals and the seconds fast or slow are posted at the clock. When clocks vary more than 10 seconds, they are set and regulated.

*Acoustical Treatment.* Accuracy and efficiency in dispatching and telegraph offices, telephone exchanges, Pullman reservation and information bureaus are promoted when the room noise is lowered by acoustical treatment of the ceilings. Material having a coefficient of absorption of 0.7 is usually satisfactory. Further reduction of noise can not usually be justified as the cost increases out of proportion to the benefits derived.

## RADIO AND CARRIER REQUIREMENTS

*Radio.* While there is a number of places where it is felt radio could be used advantageously in railroad service, its actual use has to date been rather limited.

In car retarder operation there is need for radio transmission from the hump to the locomotive pushing the train over the hump in order to direct movements, particularly during foggy or unusually stormy weather. Some trial installations have been made which indicated entirely satisfactory operation could be expected with necessary development.

On long freight trains there is need for communication from the caboose to the engine. Some of the advantages gained by the use of such communication are as follows:

Saving in coal.

In event of train separating crews are advised quickly of the trouble.

When flagmen are called in enginemen are quickly notified.

Standing trains can be quickly cut and reconnected for highway crossings.

Jammed and defective brakes can be cared for.

Orders missed by either end can be read to the other.

During fogs, heavy snows or rains, signals can be passed where otherwise impracticable.

Development work on radio sets for front to rear of train communication has been under way the past few years and sets are now available.

Some railroads have fleets of boats used in tug and ferry service in the harbors along the seaboard and on the Great Lakes. In dispatching these boats, especially the tugs, there is frequently need to communicate with the tug after it has left its pier due to changed conditions, such as late orders relative to picking up freight at intermediate points, cancellation or change of orders, etc. This communication can be obtained by means of radio but no use of it has been made by railroads to date.

A number of railroads has installed radio receiving sets for the entertainment of passengers. These sets are located in observation, club or lounge cars, some are provided with loud speakers, some with head sets. The use has been rather limited and installations have only been made on the higher class trains.

The matter of commercial radio telephone communication to passengers on trains has received some attention but it is felt it is essentially a matter for consideration by commercial companies.

*Carrier.* Carrier telegraph or telephone systems have not been used on railroad lines in the United States on account of cost considerations. The Canadian railroads, however, have installed an extensive circuit mileage of carrier.

## OUTSIDE PLANT REQUIREMENTS

The factors underlying the design of communication pole lines of railroads are somewhat different than those involved in the design of lines of commercial companies. The latter usually have alternate routes in case of failure while this is almost always the exception with a railroad. Then, too, the railroad communication pole line ordinarily carries the automatic signal wires, the failure of which causes serious interference with train operation. For these reasons, railroad pole lines require a higher strength factor than the commercial lines. The problem is essentially one of engineering design. The proper loading assumptions based upon the maximum velocity of wind and coating of ice for the territory involved are determined. From these the required number and size of poles per mile for any desired factor of safety may be determined. The Telegraph and Telephone Section of the American Railway Association in its basic rules and pole tables recommends a minimum factor of safety of two.

### CONCLUSION

From the above it may be noted that the communication requirements on a railroad are extensive and exacting.

In order to construct, maintain and operate such a plant efficiently a separate communication department is required, provided with the necessary technical engineers, construction men, wire chiefs, traffic men, etc.

The communication departments of the railways of the United States, Canada and Mexico are organized under the American Railway Association into a Telegraph and Telephone Section. This body, through its committees, prepares and promulgates standards for construction, maintenance and operation. By its work great strides have been made in standardization of railroad practises with ensuing economy.

Looking to the future, the ideal to which the railroad communication service should strive is uninterrupted and prompt telephone and/or telegraph service from any point on the system to any other point.

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## Discussion

For discussion of this paper see page 294.

# Communication System on the Pennsylvania Railroad

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***Synopsis.**—The paper gives a description of the communication services required for operation of the Pennsylvania Railroad and for the convenience of its patrons, also a description of the company-owned outside plant required to provide the service, together with tabulations showing the magnitude of some classes of business handled and plant involved.*

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## GENERAL

THE magnitude and importance of the communication system required for the safe and efficient operation of a large railroad system are seldom appreciated by those not closely in touch with it.

Unlike most railroad companies in this country, the Pennsylvania owns, maintains and operates its pole lines, conduit lines and cable system, and where wires or cables of commercial telegraph or telephone companies are on the railroad right-of-way, it is on a rental basis.

This paper will outline briefly the principal classes of service involved and the facilities required to provide it on the Pennsylvania Railroad.

## HISTORICAL

The development of the American railroads has been concurrent with that of the telegraph, telephone, telegraph printer and radio, and the Pennsylvania has been a pioneer in the experimental development and application of each form of communication to its use in railroad operation.

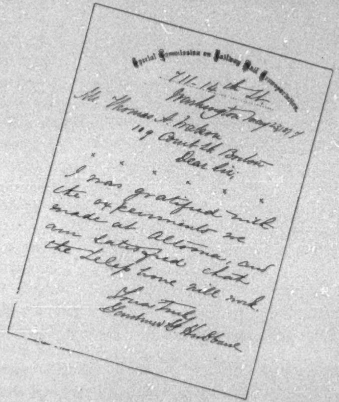
The Morse telegraph was introduced about 1844; the Pennsylvania Railroad was chartered in 1846; the first time telegraphy was used to dispatch trains was in 1851, and the Pennsylvania was among the first to make use of this new means of communication.

The use of the telephone in the early days of its development, as applied to railroad work, is evidenced by an interesting letter from Mr. G. G. Hubbard, an associate of Alexander Graham Bell, to his assistant, Mr. Thomas A. Watson, regarding the use of the telephone in the shops at Altoona, Pa., May 23, 1877. See Fig. 1. This marked the first trial and use of the telephone by any railroad, and was the beginning of the system which is now probably the largest privately operated system used by any railroad in the world.

Likewise the merits of the telegraph printer, telautograph, telephone selectors for train dispatching and message circuits, loading coils for cable, and telephone repeaters for long distance service were recognized in the early days of their development, and installations of each were made at an early date.

## COMMUNICATION SERVICES

*Train Operation.* The most important class of communication service in railroad operation is the privately owned train dispatching system which is now telephone operated on 96 per cent of the Pennsylvania's mileage. The small percentage of telegraph dispatching remaining is on branch lines where the traffic is relatively light. The development and perfection of the telephone selector has made this possible and practicable. In some sections the telegraph is still retained for service in the event the telephone fails, but is seldom used otherwise. On other divisions no telegraph equipment is used at all for either dispatching or message work, both being handled by telephone.



Special Commission on Railway Mail Transportation
711-14th St.
Washington May 23 1877
Mr. Thomas A. Watson
109 Court St. Boston
Dear Sir,
* * * * * *
I was gratified with the experiments we made at Altoona, and am satisfied that the telephone will work.
Yours Truly
Gardiner G. Hubbard

Courtesy—American Telephone and Telegraph Co.

FIG. 1—PORTION OF LETTER FROM G. G. HUBBARD TO T. A. WATSON, MAY 23, 1877, REGARDING TESTS WITH TELEPHONE AT ALTOONA SHOPS

The dispatcher, normally located at division headquarters, is provided with selector calling keys which enable him to call selectively any one of the many telephones at the interlocking or block stations on the division or section over which he is dispatching trains. The usual arrangement at the dispatcher's office also includes a loud speaker, with provision for a head receiver if desired, and a breast transmitter with foot

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*Pennsylvania Railroad Co., Philadelphia, Pa.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

switch or hand key for transmitter cut out. The receiver is always on the line so that any party on the line can get the dispatcher immediately without signaling if the line is not busy.

The exact time the different trains, both freight and passenger, pass the different interlocking and block stations is reported to the dispatcher immediately and he records this on his train sheet.

When everything is working normally, the dispatcher has little to cause him worry, but trouble which changes the spacing of trains, diversions from their normal routes, running against current of traffic, changes in meeting and passing points and many other special conditions require a clear head and quick and accurate decisions; the quality of the transmission to the end of his circuit must be within certain limits so that there is no misunderstanding of orders or information given. Train orders are always repeated back and must be correct before they are put into effect.

The dispatching circuit is used exclusively for that purpose and in event of trouble on it, other circuits are taken to make it good. In the event of storm prostration or other emergency causing interruption of service, the dispatching circuits are always the first to be restored.

Interlocking and block stations are usually equipped with a switching cabinet mounted on a table in front of the operator. All the lines entering such an office for service terminate in this cabinet equipped with keys, jacks and signals so that the local telephone set may be connected to any line by merely pushing a key. Jacks and patching cords are provided so that any line may be connected to any other line in the panel. Test and patch panels also are provided at certain points, where all lines would be available for testing and patching.

Block circuits, which are local circuits extending in each direction between adjacent block and interlocking stations, are used by the block operators to pass information regarding approaching and passing trains, and are considered about as important as the dispatching circuits from an operating standpoint.

Signal bridge telephones are installed in the familiar shelter boxes at practically all signal bridges along the main line and at each end of passing sidings, and are connected to circuits to adjacent block or interlocking stations. These circuits are used by conductors and enginemen of trains in ascertaining from the signalman the condition of the block and in obtaining permission from him to enter the main track from a siding or branch line track where there is no block or interlocking signal to govern.

*Telephone Message.* Telephone message circuits which correspond closely to the dispatching circuits in their characteristics, are generally used for handling intra divisional messages. They are usually equipped with selectors and extend to the same points for service as the dispatching circuits, and in some instances also connect to stations.

In case of trouble on the dispatching circuits between certain points, the message circuit is broken at the patch panels at each end of the section in trouble and is used to make the dispatch circuit good until the trouble is cleared on the dispatching circuit.

The message circuit usually is phantomed with the dispatching circuit to provide additional telephone tie or trunk circuits, and they are simplexed or composited for additional telegraph or printer circuits between the different division headquarters.

*Telegraph and Printer.* Message and report business between the general office, regional and divisional headquarters is handled largely by Morse and printers.

A special type of report used in car tracing and reconsignments is important in connection with certain classes of freight shipments and is known as a passing or consist report. These are sent from certain important yards to car trace bureaus at regional headquarters and show the car numbers, lading, consignee, destination, date and time of passing certain points for important freight enroute. Many of these reports are handled on the printers.

Both Morse and printers are operated duplex on the through service, using telegraph repeaters when and where required.

Commercial telegraph business for the convenience of the public is handled at practically all stations, through arrangements with the commercial telegraph companies.

*Emergency.* In territory where the circuits are all in cable, the only access to them for emergency service between the stations and interlocking or block stations is where they are terminated on binding posts in the telephone shelter boxes. This provides for connections from along the track to block and interlocking stations and other points on the system. These circuits are independent of the regular block or signal bridge circuits and generally terminate in the block office switching cabinet where they may be switched to other circuits depending upon nature of service desired. It is considered necessary to provide this service which cannot be interrupted by any other telephones in the block, and has proved very efficient in emergencies.

Another class of emergency service which is used in event of prostration of lines between general office and regional headquarters or between division headquarters includes the tie lines for telegraph or telephone service to the adjacent offices of the commercial telegraph and telephone companies. These arrangements make it possible to establish connections to the distant points without delay, providing that the commercial lines are not similarly affected.

*Time Service.* One very important detail in connection with train operation is correct time which is available at all points where trains are operated and reported. This requires clocks with a relatively high degree of accuracy. In some places the trains are on such short headway that the passing time report includes the seconds as well as the hour and minute.

To insure that the clocks are all in step, official time signals from the U.S. Government Naval Observatory at Washington, D.C., are sent out on the system twice daily, at noon and at midnight, and the clocks are set accordingly. Special circuits for telephone and Morse are set up for this purpose.

*Telephone Exchanges.* Private branch exchanges for intercommunicating service and for service to and from the public are installed as shown in Fig. 2. In size these vary from the small one-position manually operated board to the largest manual board on the system at the general office, Philadelphia. This is a 23-position board equipped with 1,240 telephones, 38 long-distance trunks, 170 tie lines and 106 trunk lines to the telephone company's central office.

The trend is toward machine switching equipment, replacing the manually operated boards, as is evidenced by the changes which have been made in many of the most important exchanges on the system, including Chicago, Pittsburgh, Harrisburg and New York. A machine switching exchange is being installed in the new station at Philadelphia which will consolidate the 23-position manual exchange, an 8-position manual board, a 100-line automatic and several smaller exchanges. This type of exchange provides dial equipment for all intercommunicating service which is available 24 hours per day for any sudden emergency which would create a peak load, an advantage which is readily appreciated, and provision is made for tie line dialing for calls to many of the railroad exchanges quite widely separated. Outgoing calls to the Bell system also may be dialed or restricted as desired. Incoming calls from the public and the longer trunk line calls will be handled manually. The trunk calls are handled manually as more efficient use can thus be made of this part of the plant which represents an appreciable investment than if handled on a dial basis. Preferential and emergency calls can thus be made.

The consolidation of exchanges in the larger centers has been under way for a number of years in the interest of economy, improved service, better transmission and also for the benefit of the public, as it simplifies the directory listing. Evidence of this trend is indicated by the reduction of the number of exchanges on the system from 192 in 1925 to 124 in 1932 prior to the consolidation at Philadelphia.

A modern machine switching private branch exchange is installed in New York. There are about 600 subscribers' lines, 60 trunks and tie lines to other P.R.R. exchanges, and 80 trunks to the Bell central office. This exchange provides telephone service for the railroad in the New York district where formerly there were several exchanges, each with a different directory listing.

*Train Information.* A special class of telephone service and equipment is provided at certain of the larger stations to furnish information to the public regarding passenger train service, such as the arrival and departure of trains, train connections, through service over foreign lines, rates for transportation, Pullman fares and so forth. In the Pennsylvania station New York twelve operators are at times kept busy answering such inquiries.

Provision is made for a transfer of incoming calls to the regular private branch exchange or to the Pullman reservation equipment when so requested by the calling party. In case a call is made originally to the main private branch exchange and train information is desired, the call may be transferred.

Telautographs and printers are used in a number of the larger stations for the purpose of giving information regarding trains. This information is used by the attendants at such locations as information desks, local block and interlocking stations, station master's office, bulletin boards, baggage offices incoming and outgoing and mail rooms. The principal information so handled is regarding time of arrival and departure of trains, track on which they will arrive and so forth, and is transmitted from the local train director's office or the terminal block or interlocking stations. This is essential information for the public. They also serve for the proper receipt and dispatch of baggage, express and mails. Their importance is probably greatest during the holiday rushes, vacation periods, during storms when train delays are imminent and inquiries from the public are most numerous, also during special events when extra or special trains are provided.

*Pullman Reservations.* In the larger stations such as Philadelphia, Chicago, Pittsburgh and New York the Pullman reservations are all made by telephone from the ticket windows in the stations, uptown ticket offices or consolidated ticket offices to the reservation room. The diagrams for all trains for the current date and for advance reservation are available in front of operators, provided with special equipment. Different sections of the railroad and different foreign line connections are handled at different reservation desks.

The installation in the Pennsylvania station New York shown in Fig. 3 is the largest and most modern, and is the result of experience over a number of years.

Ticket windows in the stations and other ticket offices in the city are provided with dial telephones connected directly with this system so that the ticket seller can call the particular section or table handling the diagrams for the trains desired. Incoming calls from the city or public are received on a special manual board where an operator will question the calling party as to reservation desired, and then will switch the call to the proper table to handle that class of reservation.

Many reservations are made by telegraph from out of town points. To handle this business without delay a pneumatic tube is used between this office and the railroad telegraph office. There is sufficient reservation business between Philadelphia and New York to assign one telephone trunk exclusively for this business.

*Messages to and from Passengers Enroute.* Through arrangements with the commercial telegraph companies,

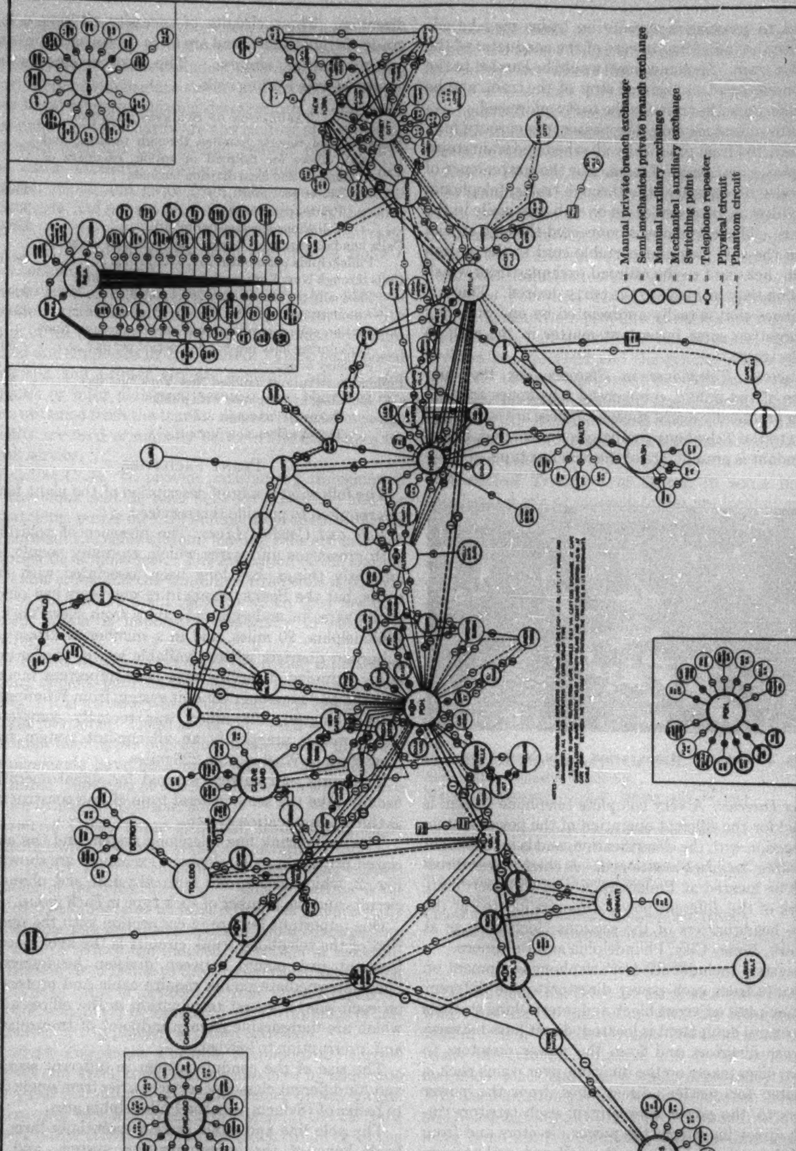
Manual private branch exchange
Semi-mechanical private branch exchange
Manual auxiliary exchange
Mechanical auxiliary exchange
Switching point
Telephone repeater
Physical circuit
Phantom circuit
NEW YORK
JERSEY CITY
PHILA
BALTO
WASH
ALTOONA
PGH
BUFFALO
CLEVE LAND
DETROIT
TOLEDO
CHICAGO
ST LOUIS
CIN-CINNATI
LOUIS-VILLE

FIG. 2—PRIVATE TELEPHONE EXCHANGES AND CONNECTING TRUNK AND TIE LINES

messages to passengers enroute on trains may be addressed to the individual in care of the conductor of the particular train. Such messages would be handed to the train conductor at a scheduled stop of the train, and he would then page the train for the party addressed.

Likewise messages from the passengers enroute may be transmitted from practically all scheduled train stops.

*Telephones on Limited Trains.* For the convenience of the traveler on certain of the through trains, telephones are provided in the observation or club cars while in the terminals. This telephone is connected through special jacks on the car, plug and portable cord to the station platform jacks and to the railroad exchange from which connection may be made to the party desired. This is a convenience that is really appreciated by one who may have forgotten some important matter in the rush to catch the train.

*Commercial Telephones in Stations.* For the convenience of the public, commercial telephones are provided in practically every station. These are connected directly to the Telephone company's system and, unless an attendant is present, are of the coin box type.

FIG. 3—PULLMAN RESERVATION ROOM NEW YORK

*Power Director.* A very complete telephone system is provided for the efficient operation of the power system in connection with the electrification, and is independent of the other facilities mentioned. A chief power director will be located at Philadelphia who will coordinate the work of the different power directors located at the division headquarters of the sections electrified; as at New York, Jersey City, Philadelphia and Baltimore.

The system includes selector telephone equipment on the circuits from each power director to the different substations and adjacent block and interlocking stations where control equipment is located; direct lines between the power directors and from the power directors to the train dispatchers on the divisions over which each is responsible for service; direct lines from the power directors to the power company in each territory involved; direct lines from the power directors and from the chief power director to the railroad exchange in that district; and patrol circuits from the shelter boxes at the signal bridges along the railroad to the power directors. These circuits of necessity all have a high grade of transmission and are all in cables with the other communication circuits. The longer circuits are equipped with loading coils.

TABULATION OF BUSINESS HANDLED

| | |
|---|---|
| Messages and reports handled through terminal and relay offices for railroad operation, exclusive of commercial and local division business | |
| Morse per month | 400,000 |
| Printer per month | 500,000 |
| Telephone message per month | 108,000 |
| Calls handled through General Office manual exchange | |
| Philadelphia per month | 480,600 |
| Calls through New York semi-mechanical exchange | |
| Manually per month | 228,000 |
| Automatic per month | 324,000 |
| Information calls regarding train service through New York during busy pre-holiday period per day | 5,000 |
| Per busy hour | 700 |
| Pullman reservations handled New York busy day | 9,400 |
| Including by telephone with public | 2,600 |
| Telegraph message | 450 |
| Ticket sellers New York | 6,350 |

## PLANT FACILITIES

The following is a brief description of the plant facilities required to provide this service.

*Pole and Conduit Lines.* The presence of pole lines with crossarms and wires which, to many people, are unsightly things, has long been associated with railroads, but the Pennsylvania in recent years has placed all its wires in underground cables from New York to Philadelphia, 90 miles, and in a number of urban and suburban districts where available space, appearance, and continuity of service have been important factors. The six- and nine-duct conduit system from Wilmington to Washington, 108 miles, was recently completed, which makes practically an all conduit system from New York to Washington, 226 miles.

The wires and cables required for signal operation usually take the same general type of line construction as the communication system.

The main trunk line telephone system and the associated private branch telephone exchanges are shown in Fig. 2, which also shows both physical and phantom circuits and the number of each type in each group.

One important feature in connection with the operation of the telephone trunk circuits is the avoidance of frequent test points between division headquarters. Such intermediate points require cable and protection on each side, also test termination in the offices all of which are undesirable from standpoint of transmission and interruption to service.

The size of the conduit system in different sections and for different classes of service varies from single duct to banks of 78 ducts as in the Philadelphia area.

The pole line and cable system essentially form the back bone of the communication system, and, on account of its location along the railroad right-of-way, is exposed to many operating conditions to which the commercial lines are not subjected, as alternate routes cannot be chosen by the railroad to obtain more favorable conditions. These include routes closely paralleling many streams where glaze storms and fog are prevalent, close to oil refineries causing deterioration of open wire conductors and line hardware and coating of line insulators with resultant line leakage, cement plants which also cause excessive coating of insulators and line leakage, smoke and gases from coke ovens and industrial plants, and not the least of the troubles is the soot deposit on the insulators, telephone equipment and terminals due to the smoke from the engines along a busy section of railroad.

*Superposed Circuits.* Practically all the physical telephone trunk circuits shown in Fig. 2 together with many of the message and dispatching circuits are phantomed and simplexed or composited. These superposed telegraph and printer circuits generally are used for through or inter divisional service. The phantom circuits obtained from the trunks, dispatching and message circuits are used principally between the exchanges for trunk service.

*Loading Coils.* To provide satisfactory transmission for the trunk and tie lines between exchanges and for dispatching, power director and message circuits operating through the cable system, loading coils are installed at intervals of 6,000 feet. The insulation of the loading coil cable stubs and the windings of the coils is equivalent to that of the main cable to which they are connected, which is important, especially in electrified territory.

*Telephone Repeaters.* In order to provide satisfactory talking circuits between the principal exchanges shown in Fig. 2 it is necessary to install telephone repeaters at certain locations. These are of the "cord circuit" and "through line" types depending upon service involved. Arrangements have been made for the installation of "terminal" repeaters at Philadelphia which will improve service to and through that point.

*Armored Cable.* Paper-insulated, lead-encased cable protected with a double armor of galvanized tape is a more recent type of construction used along certain sections of a-c electrification. This protection is intended to eliminate or at least reduce very appreciably the trouble due to bullets in aerial cable construction, and also to reduce the induced potentials in the communication circuits due to the a-c electrification. When this type of cable is installed in underground construction the armor will be protected with wrappings of impregnated jute to prevent or retard corrosion.

*Portable Telephones.* Portable telephones are carried on work and wreck trains and are also used by telephone and signal maintainers and maintenance of way gangs. Where open wire line construction is used, the fish pole type of connection is made to the block circuit or to the train dispatcher's circuit depending upon the nature of the business. Where cable construction exists, the connections are made at the shelter boxes as above mentioned, the circuit being extended from the shelter box to the location where the telephone is to be used by means of insulated wire laid on the ground. Special arrangements are necessary to use these on simplexed circuits to avoid grounding the circuit when the set is placed on the ground.

*Radio.* Interest in radio for railroad operation has been manifested by the company for more than twenty years, and a number of experimental installations have been made, including land stations, on passenger trains, freight trains and on tug boats. At present there are no radio installations on the system.

*Testing Facilities.* To maintain the plant in good operating condition, proper wire chief's testing facilities and personnel are provided at the different regional and division headquarters and the general office, also such portable testing equipment as necessary including: meggers, bridges, telephone transmission testing sets and so forth. Routine testing for condition of plant permits location of defects in many cases before actual trouble develops.

*Acoustical Treatment of Offices.* In some instances the dispatcher's or message offices are located adjacent to the tracks or facing busy streets where traffic is heavy, resulting in excessive and objectionable noises in the operating rooms. In other cases the room noises, on account of the number of individuals or character of their work, are excessive. These conditions in several cases have been appreciably improved by the acoustical treatment of the ceilings, resulting in more satisfactory working conditions and a better grade of work.

TABULATION OF PLANT FACILITIES IN SERVICE

| | | |
|---|---|---|
| Pole line with wires and cables | 10,339 | miles |
| Open wire | 106,644 | " |
| Underground cable, exclusive of laterals | 670 | " |
| Aerial cable, exclusive of laterals | 230 | " |
| Main underground conduit, principally 6- and 9-duct | 379 | " |
| Cable conductors in service, exclusive of laterals | 58,000 | " |
| Superposed phantom telephone circuits | 10,000 | " |
| Superposed telegraph and printer circuits | 32,000 | " |
| Telephone repeaters "through line" | 10 | " |
| Telephone repeaters "cord circuit" | 8 | " |
| Offices for handling railroad messages and reports and commercial telegraph business | 1,337 | " |

## CONCLUSIONS

It is obvious that there are many and varied problems which develop in connection with the communication system which extends through the section of country where the greatest industrial and power development has taken place and where traffic is probably heaviest. The electrification project in itself between New York and Washington, with the many communication problems, is no small assignment, but the time and space allotted will not permit of a discussion of those features.

The underground system of conduits and cables extending through and between the different cities and towns is subject to many conditions requiring special consideration from standpoint of construction, maintenance and operation.

The increasing use of the telephone for long distance business between widely separated points on the system, with alternate routes where available, and the increasing use of printers, requires a high grade of plant and its maintenance for satisfactory service.

From the foregoing it may be seen that an attempt is being made to provide a communication system that will keep pace with modern developments in the art and which is considered a necessary adjunct to modern railroad operation.

## Discussion

### COMMUNICATION REQUIREMENTS OF RAILROADS

(Niesse and Thayer)

### COMMUNICATION SYSTEM ON THE PENNSYLVANIA RAILROAD

(Forshee)

**W. H. Arkenburgh:** Certain information is given in this discussion which was not available to the authors of the paper at the time that they prepared it.

The General Electric Company has recently developed a system of communication for freight trains. This can be used to communicate either from front to rear end or from a train to a wayside point or from train to train. Fig. 1 illustrates the principal features of this system. The rails of the track are connected through impedances to any convenient ungrounded conductor parallel with the track. These impedance couplings are spaced approximately 1,000 feet apart. This distance will vary with local conditions. As shown in the figure the impedance consists of two condensers in series so arranged as not to shunt the signal track circuit. Where track circuits are not used this precaution is not necessary and other forms of impedance might be used. Upon the value of the impedance in effective ohms, depends the attenuation of the system which in turn determines the distance over which it will operate.

The equivalent of extremely simple carrier current receiving and transmitting sets are mounted on the locomotive and on the caboose of each train. These sets are connected in each case to inductor coils which are mounted just above the rails at minimum allowable clearance. These coils are so connected that instantaneous induced current values will be in the same direction in each rail. Automatic volume control is included to compensate for variation in distance between inductor coils and rails due to action of springs on rolling stock.

Electrical oscillations set up in the inductor coils by a transmitter will cause corresponding oscillations in the rails and thus in the system comprising the rails, the impedance couplings and the paralleling conductor. These oscillations are thus propagated over a predetermined distance and can be picked up from the rails at any point within that distance by any other set of inductor coils. In this manner two-way communication may be had between the front and rear of a freight train or between two trains if within the proper distance. Communication may also be had between trains on adjacent tracks or the system may be so arranged that there will be no cross talk. If receiving and transmitting apparatus is connected into the paralleling conductor at any wayside point communication may be had between such point and any train within a predetermined distance.

Provision is made for the protection of automatic block signal and other circuits. There will be no interference with the operation of automatic block signals or adjacent telegraph and telephone lines. If desired, any adjacent line wire may be used for coupling to the track. Thus advantage may be taken of wires normally used for the control of automatic block signals, for telephone or telegraph and also for power transmission.

Inasmuch as this system does not in any way depend upon space radio propagation it can be installed and operated without a license from the Federal Radio Commission.

**W. A. Jackson:** Mr. Forshee's paper gives me an opportunity to refute the statement that is so often made that the railroads are not progressive. So far as communication service is concerned, they have taken advantage of practically everything that is available. While Mr. Forshee's paper covers only the Pennsylvania System, with a few more or less minor modifications, it might be just as well applied to the railroad with which the writer is connected—the New York Central. The same remarks probably would be applicable to most of the other large railroad systems as well.

**H. W. Drake:** Two points may properly be emphasized at this time.

The first of these has been touched upon by Mr. Jackson and relates to the reproach so often leveled at the railroad managements to the effect that many of their present difficulties are due to failure to take advantage of improvements which might be obtained through scientific research and engineering development. I feel sure that any unbiased person reading these papers and the ensuing discussion will agree that there is little or no foundation for such a reproach in connection with the communication systems of the railroads.

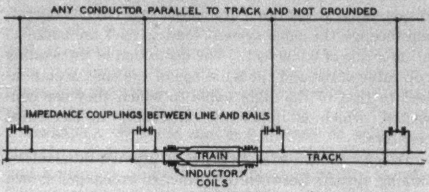
ANY CONDUCTOR PARALLEL TO TRACK AND NOT GROUNDED
IMPEDANCE COUPLINGS BETWEEN LINE AND RAILS
TRAIN
TRACK
INDUCTOR COILS

Fig. 1—General Electric Train Communication System

In the second place, the importance of the telegraph in railroad communication systems should be emphasized. We all recognize the advantages of the telephone in meeting many requirements of railroad service and this sometimes leads to a tendency to ignore the situations to which telegraphy is better adapted.

In support of this, attention may be called to the fact cited in the Niesse-Thayer paper that in a large railroad system, the number of telegraph messages may average from twelve millions to thirty-six millions per year. Further evidence appears in the table in Mr. Forshee's paper indicating that in addition to the very widespread use of the telephone on the Pennsylvania System, about eleven million telegraph messages per year are handled on railroad circuits. It is the writer's recollection that the latest report of the Interstate Commerce Commission shows that about 40 per cent of the railroad mileage of this country is still operated by telegraph. To these facts may be added mention of the suggestions made at various times in the past that careful engineering studies of the possibilities of telegraphy would often bring forth an economic solution of numerous problems which arise in railroad communication work.

Some mention has been made of the facilities made available to the railroads by the telephone companies. Without detracting in any way from the splendid work that has been done along these lines, it may not be out of order to emphasize also the similar provisions made by the telegraph companies in furthering the efforts of our railroad friends to provide satisfactory communication systems.

**I. C. Forshee:** The limitations of time and space did not permit of detail descriptions of any of the various services or facilities mentioned in the paper.

Since the plan in Fig. 2 was drawn, the underground conduit and cable between Wilmington and Washington have been completed and placed in service. This included telephone repeaters at Baltimore and provided an increased number of telephone trunks through the district.

The Wilmington-Washington cable is under constant gas pressure, divided into sections and equipped with alarm gages and alarm circuits which operate when the pressure drops in any section due to cable sheath faults. The cable on the New York Division is being similarly equipped.

Tie and trunk line dialing are being used to speed up the service in a number of exchanges where full automatic or semi-mechanical equipment are in service.

Since the paper was written metallic telegraph and printer circuits have been placed in service between New York and Philadelphia, with metallic repeaters at Philadelphia for direct operation with grounded circuits which extend to other points on the system, as from New York to Washington, Pittsburgh and Chicago.

The railroads recognize the assistance given them by the commercial telephone and telegraph companies in plant development, maintenance and operation to which Mr. Drake referred and for which the railroads are duly grateful. There are many conditions which are peculiar to the railroad communication plant, however, for which the railroad engineers must develop their own solutions.

The telegraph, as Mr. Drake mentioned, is still used extensively for handling messages and reports between divisional and regional headquarters and between the general office and those points, and probably will continue to be so handled for some time to come, but the local message and report business on the divisions is very largely handled by the telephone and printer.

The a-c electrification has developed many interesting problems in the railroad communication plant, but a description of them is hardly feasible in this paper and discussion. It may be said, however, that the communication system is operating satisfactorily.

Train announcing systems which were popular a few years ago are now conspicuous by their absence, and in many of the larger stations one never hears a train announced either on its departure or its arrival.

# Railroad Signaling and Train Control

BY R. B. AMSDEN* and W. M. VANDERSLUIS*
Non-member Fellow, A.I.E.E.

SOON after the first public railways were built in England early in the nineteenth century, their managers discovered the need of some method of conveying information and instructions to train crews. The first signals used were crude affairs of many shapes and colors and confusion naturally resulted because of different meanings having been assigned to them on the different roads. The first real improvement was made in the year 1841 when C. H. Gregory adapted the semaphore to railway uses.

Tradition says that the semaphore, which consists merely in the attachment of a movable arm or blade near the top of a pole, was invented by a talented Greek named Polybius, several hundred years before Christ. But the idea doubtless came from the original source of a man making signs by moving his arms. The Romans, and afterward the French, Germans, Russians and English, employed it for both civil and military purposes before the invention of the electric telegraph.

As applied to railroads, the semaphore consists of a blade, three to four feet long, attached to a spectacle in which are mounted colored glasses behind which a lamp is placed for night indications. When the arm is in the horizontal position, with red light, "stop" is indicated. When the arm is 45 degrees above the horizontal, with yellow light, "caution" is indicated. When the arm is 60 degrees below the horizontal or 90 degrees above the horizontal, with green light, "proceed" is indicated.

### THE TELEGRAPHIC BLOCK

Charles Minot, superintendent of the Erie Railroad, made the first practical application of the Morse telegraph for the sending of train orders, in 1851. With the first train order came telegraphic train dispatching which offered an effective means for reducing the delays incident to operation under timetables. Two forms of train orders are in use, form "31" and form "19." Form 31 is receipted for in writing by the conductor of the train addressed. Form 19 is receipted for by the station operator, who is responsible for the delivery of the order to the conductor and engineman of the train addressed. Because of this difference in delivery, a moving train is required to stop for a 31 order but need only slacken speed for a 19 order.

Two train order signals are provided at each station, one to govern the movement of trains in each direction for single or double track. These are usually placed on one mast and the semaphores are generally manually operated by levers in the station. They are held normally "clear" and are placed in the "caution" or "stop" position when an order is to be delivered to an approaching train. If a three-position indication is employed, the 45-degree position usually signifies that a 19 order is to be received and the horizontal position indicates a 31 order. In two-position signaling, the horizontal position means either a 19 or 31 order.

### MANUAL BLOCK SIGNALING

With the space interval method, train movements are directed as in the time interval method, by timetables and train orders, and in addition, by block signals. Space is maintained between trains by dividing the track into sections with fixed signals to govern the movement from section to section. Blocks may vary in length according to traffic requirements.

In the manual block system trains are spaced by the display of manually operated signals based on information conveyed by telegraph, telephone or bell code between two stations. Signals govern the use of blocks only and do not supersede the superiority of trains or dispense with the use or observance of other signals, unless otherwise provided. Several systems of operation are in use; absolute block for all movements on the same track; absolute for opposing, and permissive for following movements on the same track; absolute block or permissive block for following movements on double track.

The block signals are held normally in the "stop" position and are cleared only on the approach of a train when the block ahead is clear and are restored to the normal position after the train has passed. A "proceed" indication allows a train to proceed only if it has authority by timetable or otherwise and gives exclusive right to the track to the next block signal. Each block operator is ordinarily required to keep a record of passing trains. The simple manual block system is operated by rigid rules but without electrical or mechanical check on the block operators.

### CONTROLLED MANUAL BLOCK SYSTEMS

Several types of controlled manual block signaling are in use, all of which are operated on the principle that the cooperation of two persons, one located at either end of a block, is necessary before any signal can be cleared to admit a train into the block. Although this system is operated manually, electrical and mechanical means are used to provide more or less complete control. The more highly developed systems employ either short sections of track circuits at stations or complete track circuit control which provides protection against open switches, broken rails, or cars inside of clearance points and gives the block operator a continuous indication of the condition of the block.

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

Approach and advance block signals are often used in controlled manual block signaling. The installation of an advance block signal permits trains to use the switches between it and the block signal and expedites the movement of trains from block to block when traffic is heavy. Power-operated approach signals may be provided which indicate caution at all times, except when the block signals are clear, switches set for main track, and the section between the approach and block signals is unoccupied. Outlying switches between block stations may be electrically locked and controlled by the operator in the block station to the rear.

In controlled manual block operation, the block signals govern the use of the blocks and their indications supersede timetable superiority and take the place of train orders, unless other provisions are made. These signals do not, however, dispense with the use or observance of other signals which may be required.

### Automatic Block Signal Systems

Automatic block signaling is controlled entirely by the condition of the track and eliminates the human agency. The fundamental requirement of any automatic signal system is that a failure of any sort on account of interruption of power, broken rail, broken wire, or other defects of apparatus, will result in the signals immediately displaying their most restrictive indications. The design of all modern signal equipment is based upon this fundamental requirement.

The Standard Code of the American Railway Association, Block signal and Interlocking Rules, adopted January 17, 1928, shows the recommended signal indications, names and aspects, to which are added the rules governing typical color and position combinations. The roads usually follow the A.R.A. recommended practises as far as possible, but in some cases it is considered necessary to amplify the indications to suit special requirements on the various lines.

The conditions which determine the length of the block sections and consequently the number of trains that can be run in a given time are: (a) the maximum speed; (b) the braking power and consequent distance required in which to stop a train running at maximum speed; (c) the grade and alinement of the track; (d) the time required for the signals to change indications; (e) the length of the trains and (f) the location of stations, interlocking plants, passing tracks, and other local conditions which cause irregular spacing of the signals.

To provide for maximum train service, it must be possible to run trains at the greatest speed local conditions will permit, the blocks being of such length as to allow this speed to be attained with safety. The engineman must be informed at all times as to track conditions ahead and if it should not be safe to proceed, he must be warned at a point a sufficient distance back of the stopping point so that the train may be brought to a stop before passing the signal. On multiple tracks signaled for traffic normally in one direction only, a stop and an approach signal indication are generally provided back of a train.

Single track signaling may consist of the overlap scheme or the absolute-permissive-block scheme. In the overlap scheme, if two trains moving in opposing directions should pass clear signals at the same instant, other opposing signals are so situated that each train will encounter a stop signal before entering an occupied block. This is accomplished by carrying the control circuits for one home signal full braking distance beyond the next signal in advance, which governs in the same direction, and making the continuity of the circuit depend upon the condition of the track section or sections ahead of the last named signal. Signals for trains moving in the opposing direction have their control circuits overlapping the next home signal in advance in a similar manner.

The absolute-permissive-block scheme of single track signaling provides head-on protection from one passing track to another passing track while permitting following movements to be made.

The leaving signal at the end of a passing track is made a positive "stop" signal while the entering signals to passing tracks and station limits are automatic permissive signals, the most restrictive indication of which is "stop; then proceed." In operation, this system is arranged so that when a train passes a positive signal at the leaving end of a passing track, the opposing positive signal is set at stop and all opposing intermediate signals assume their most restrictive indication, thus holding any opposing train at the other end of the block. The opposing signals clear after the train passes them and at the same time the train is protected from a following movement by a stop and an approach signal back of it.

### Automatic Train Control Systems

Every successful scheme of automatically applying the brakes to stop or control the speed of a train is based upon the fact that opening of the air brake pipe line results in application of the brakes. Two orders of the Interstate Commerce Commission, issued June 13, 1922 and January 14, 1924, respectively, and subsequently modified so that an engineman, if alert, may forestall the brake application and proceed without stopping, required certain railroads to select and install the type which each considered most suitable for its particular conditions, in accordance with specifications and requirements prescribed by the Commission.

Every type of train control device requires a roadside element designed to coact with an engine-carried element so as to transmit to the locomotive the conditions existing on the track as would be indicated by a modern automatic signal system. After the information is conveyed to the engineman, it may be used either to apply the brakes or to indicate by means of a cab signal, visible or audible, the conditions which exist. The devices may be classified in two general groups, the intermittent and the continuous. The intermittent may be further subdivided into the contact type and the non-contact type. The contact type depends for its operation on a physical contact between the train element and the roadside element while the non-contact type depends on an electrical or magnetic impulse without physical contact between the train element and the roadside element.

The trend has been decidedly toward the induction type of equipment and no installations of the contact type have been made on any road except the three which had such installations at the time the orders were issued. One of these subsequently changed to the induction type.

The intermittent type of device receives its control at certain fixed points along the roadside, usually at or near a signal, and is incapable of reflecting any change in track conditions between any two of the indicating points. It is an adjunct to the automatic block signal system for the purpose of preventing that class of accidents which are due to the failure of employees to observe, understand or obey signal indications. Most of the intermittent induction types in service employ an inert roadside element consisting of a laminated core upon which are mounted coils, the terminals of which are connected through a relay of the signal system. No energy is required for the track element.

The locomotive receiver carries two coils mounted on a laminated core, both of which are energized by direct current from the headlight generator. Associated with these are a number of circuits and relays on the locomotive which provide a means for producing a brake application. In all the variations of this type, the brake application is initiated by a sudden reduction of current flow in the main locomotive relay which is produced by the action of the receiver passing over the track inductor when the circuit of that inductor is open through the roadside relay in the stop position.

The basis of the continuous train control systems which have been developed, is the inductive fields produced by alternating current flowing in the rails. Collecting coils are mounted on the locomotive so as to move in the field produced around the rail. The current which is induced in these coils is transmitted to amplifying apparatus on the locomotive. The amplified current in turn controls the circuits that operate electro-pneumatic valves directly controlling the brake-pipe pressure. Circuits are also provided for a visible cab signal which constantly shows the conditions of the track. Any change in conditions in a clear block, which calls for a reduction in speed, is immediately reflected by a corresponding indication in the cab. The brakes are also applied unless properly forestalled by the engineman. Conversely, a more favorable condition in a block is immediately transmitted to the engineman and the train does not have to move under restricted speed until the next signal is reached.

The continuous type of device functions on a closed circuit, which is the basic principle of signaling, failure of any part causing a stop application. It may be used with or without permissive signals on the roadside and four railroads are demonstrating the practicability of operating without roadside permissive signals. The addition of a centrifugal governor, usually applied to the forward pony truck axle of the locomotive, provides for the automatic control of the train at the varying speeds required by different track conditions.

Alternating current of 100-cycle frequency is favored for use in the rail circuits to avoid possible interference from commercial power sources. To provide four cab indications and maximum protection against inductive interference from other circuits, a specially designed code transmitter may be used in connection with the roadside apparatus, consisting of a constant speed induction motor geared to a shaft carrying "coding" cams which operate contacts to interrupt the 100-cycle alternating current. Code frequencies of 80, 120 or 180 interruptions per minute for the approach, approach restricting, or clear indications, respectively, are impressed upon the track, depending upon the condition of the track in advance. The engine equipment is designed so as to respond only to the track current frequency when it is interrupted at the proper rate. Absence of current in the rails gives the stop indication.

Operating officers and enginemen report the safety features in cab signaling, which make it independent of fogs, storms or other obstructions to vision, as one of the greatest advantages of train control.

The first orders of the Commission having accomplished their purpose of promoting extensive development of automatic train control, an order was issued on November 27, 1928 to the effect that the railroads would not be required by order to install any more train control at present but that they are "in no way relieved from the responsibility which rests upon them to provide additional protection when needed in territory now protected by automatic signals." This leaves the roads free to use train control, cab signals, or such other means as they may see fit, to secure additional protection, particularly on dense traffic lines.

## HIGHWAY GRADE CROSSING PROTECTION

The protection of highway grade crossings is an important part of railway signaling work. Watchmen, with or without manually operated gates, are often employed at busy points in cities. An audible warning, controlled by track circuits, is objectionable in residential districts and usually does not provide adequate protection for closed automobiles in the open country. Therefore, the majority of crossing protection installations consist of visual rather than audible signals.

The requisites for automatic signals for highway crossing protection, as set forth by the American Railway Association and the American Railway Engineering Association, specify that the signal "shall present toward the highway, when indicating the approach of a train, the appearance of a horizontal swinging red light and/or disk" A Committee on Grade Crossing Protection appointed by the American Railway Association in 1930 has published its recommendations in its Bulletin No. 1. These recommendations agree with those of the National Conference on Street and Highway Safety. They are endorsed for future installations and renewal of existing devices.

### INTERLOCKING SYSTEMS

In recent years there have been many refinements in all types of interlocking. Electric detector circuits have generally replaced detector bars. Approach locking, route locking, sectional route locking, check locking, time locking and time releasing have come into general use. In addition to the mechanical locking in the machine, routes are controlled, interlocking levers are locked and switches are locked electrically by the presence of a train upon a given track circuit controlling a track relay which in turn interrupts the circuits of such locks, making them effective. As soon as a train reaches the approach circuit the route lined up is locked automatically and can be taken away only by the use of a time release which requires an elapse of one or two minutes after the home signal has been set against the train. If the train should pass the home signal the route is then locked the full distance ahead through the sectional route locking but the switches are released behind the train as each section is passed.

Where two interlocking plants are situated close together as in terminals and at tunnel, bridge or yard locations, and each has signals governing in the direction of the other on the same track, it is necessary to provide traffic locking to prevent any two such opposing signals being cleared at the same time. In electric and electro-pneumatic plants a separate lever is usually provided in the machine in each tower for each track over which reverse movements are to be made. These levers are connected with the mechanical locking in such a way as to control the direction of traffic. Bridge locking is employed in connection with movable bridges to prevent signals governing the approach to the bridge being cleared unless the bridge is locked in its closed position.

The signals used at an interlocking plant may be of either the semaphore or light type. The recommended indications, names and aspects are shown in the Standard Code of the American Railway Association, Block Signal and Interlocking Rules.

The selection of a power or a mechanical plant depends upon local conditions, among which are the distances from the tower to the switches which are to be operated and the frequency of operation. A small mechanical plant is simple to install and maintain, has few failures and is low in first cost. A power interlocking on the other hand, permits operation of switches and signals a longer distance from the tower, requires a smaller building for housing the machine, provides quicker operation, and in many cases, entails less operating labor.

Power interlocking plants are generally used at drawbridges, stations, and terminals where a mechanical plant cannot be operated to the best advantage. At large terminals, it is necessary to provide, in addition to the usual safety features, electrical indications to inform the operators of just what is transpiring at all times because they are frequently not in a position to see the tracks. The location of trains is indicated on a track diagram on which small spotlights mark the occupied sections of track, both within the plant limits and approaching the plant. Lever lights are provided on the machine to indicate when a signal is clear and whether or not a switch lever can be reversed or restored.

At passenger terminals some form of train starting system is installed to provide means of inter-communication between gateman, conductor, and towerman. Push buttons and light indicators, with or without buzzers are generally used.

There is a trend toward greater use of automatically controlled signals for governing train movements at crossings, junctions and gauntlets. Protection of this nature is termed "automatic interlocking" and the principle of operation is similar to that of automatic block signaling. The home signals normally indicate "stop" and, if conditions permit, the signal clears when an approaching train enters the approach track circuit. When the signal clears, all conflicting signals are held at "stop." Provisions are made for releasing the signal after the elapse of a time interval in case the train is delayed for switching or other purposes while occupying the approach or clearing section, so that movements can be made on the other line without flagging over the crossing. Approach signals are usually provided and a speed restriction of 10 to 25 miles per hour approaching the plant, is required.

Automatic interlockings are proving of great operating advantage and are the simplest and most economical type of signal protection which can be provided for a railroad grade crossing and other simple layouts.

### FREIGHT CLASSIFICATION YARDS

At large freight terminals a hump is provided in the yard lead track with an incline so arranged that the cars move by gravity into the various classification tracks. In past years, the majority of these gravity yards have been operated manually, men being required to throw the various yard switches and ride the cars in order to apply the brakes. The disadvantages of manual operation are that a large number of men are needed, both cars and lading may be damaged, car riders may be injured, weather conditions seriously affect the capacity of the yard, and the cost of operation is high. Power-operated switch machines are now being used which are controlled from a tower. As the cars move over the hump, the operator knows from his switch list upon which track each cut of cars should be placed and he operates the switches accordingly.

Power-operated car retarders are also controlled from the tower. A set of brake shoes is placed along each side of and parallel with the rail and arranged to move towards the rail to clamp the sides of passing car wheels to retard the motion of the car. The control lever is arranged to give three degrees of retardation, as well as to open the retarder for the movement of the car. In order to prevent damage in case cars get through the retarders without sufficient retardation, power-operated skate placing machines are installed where necessary to place a skate on the rail ahead of a car to arrest its movement.

The control and operation of the switches, retarders and skate machines may be entirely electric or electro-pneumatic, all control levers being in the same machine located in an elevated tower so that the operator of each group can see the yard and observe the location of the cars as they pass through the switches and retarders. Suitable flood lighting is provided for night operation. The several operators are directed by a yard master by means of a loudspeaker in each tower. Pneumatic tube and teletype systems are used in sending switch lists to and from the yard offices.

While in some respects the signal appliances employed at hump yards are similar to those used at interlocking plants, there are several points of difference. There is no interlocking of the levers and the signals are few in number and have special indications. The signals may be of either the semaphore or light type. One signal is usually provided for each direction at the top of the hump with repeater signals in the yard as required. For movements over the hump the usual indications are "stop," "hump slow," "hump fast" and "back-up." The indications of the signal governing movements in the opposite direction, known as the "trimmer signal," are "stop" and "proceed."

Car retarder installations are improving service to shippers and reducing operating expenses by reducing motive power expense, increasing car capacity, reducing delays and personal injuries, reducing damage to equipment and lading, and consolidating classification yards.

## Remote Control of Outlying Switches and Signals

The need for reducing the delay time of trains on the road has resulted in the development of a low-voltage electric switch and lock machine for application to outlying switches at ends of double track, passing tracks, junctions and entrances to yards where they may be remotely controlled by an operator or other attendant at a station or interlocking tower a mile or more away. The switch points are prevented from being moved while engines or cars are on or adjacent to the switch through the medium of electric track circuit control. Signals control train movements over the switch and provide additional safety in that a train taking siding must pass the fouling point before another train can get an indication to proceed on the main track. If near an interlocking plant the apparatus required for outlying switch control may be operated by levers in the interlocking machine. Where installations are made adjacent to manual block or station offices, a small table machine, equipped with locking devices and indicators is used for the lever control of the switch and signal units. The usual approach, detector and route locking used in interlocking practise can be provided. Such an arrangement allows trains to enter or leave sidings or yards, or to turn out at junctions, without stopping or reducing speed below that safe for passing through the turnouts.

## Train Operation by Signal Indications

Although block signals were first installed as a safety measure to supplement the train order system owing to the weak link of human fallibility, the remarkable advance in the art of signaling and demonstration of the reliability of signal indications soon relegated the train order to a distinctly inferior position. The development of directional traffic control between interlocking plants and the signaling of intermediate tracks for operation in either direction, together with the remote control of outlying switches, brought about the operation of trains by signal indication only, on both single and multiple tracks. This was first done locally between interlocking or block stations and permitted the utilizing of both track and equipment to their full capacities by shortening headways between trains and operating superior trains around inferior trains without stopping, thus avoiding clearance time for inferior trains and long waits at passing points when the overtaking train was delayed. This arrangement was extended to include several adjacent sections, all operated under the direction of the dispatcher without the use of written train orders or train rights by timetable or direction. It resulted in the handling of increased traffic at higher speeds and postponed the construction of additional tracks.

## Centralized Traffic Control

To reduce the cost of operation and secure a more flexible layout a system of control circuits known as "centralized traffic control" has been designed which reduces the number of line wires to a minimum and places the control of all switches and signals of an entire district or division directly in the dispatcher's office. The direct wire systems, which are considered more economical for distances of only a few miles, require two or three wires for switch and signal control and additional wires for the approach indications which are essential if unnecessary stopping of trains is to be avoided. For long distances, and especially when a number of groups of switches and signals is to be controlled, a code-relay system is used which requires but two wires, irrespective of distance. By the transmission of interrupted currents which form codes similar in character to Morse telegraph signals consisting of dots, dashes, and spaces, a selection of the proper relays is effected to control the operation of switches and signals at any desired location and to transmit back over the same two wires light indications showing the operation of corresponding switches and signals and whether the track circuits are occupied or unoccupied.

The control equipment consists of a machine containing levers for operating the switches and signals and having a track model suitably equipped with colored lights to aid the operator in visualizing all train movements under his control. An automatic train graph records the movement of each train on a graphic train sheet. These indications are made possible through the medium of the track circuits.

The switches at points along the right-of-way are operated by electric switch machines, similar to those used at interlocking plants, except they have a dual-control so that they may be operated electrically by the dispatcher for regular moves or mechanically by the train crew for switching moves or in case of emergency. The dispatcher's consent must be secured, however, to operate any of these switches by hand. Telephones are provided for use of trainmen in communicating with the dispatcher.

The switch machines and the signals at the end of a passing track, at a junction or a crossover, form a controlled group which is essentially a small interlocking plant. A signal cannot be cleared until the approach track circuit is occupied and the switches are properly set. Adjacent groups are electrically interlocked with each other to prevent conflicting signals being cleared either by the automatic operation of the signals or by any manipulation of control levers that the dispatcher may make. Approach locking is provided to prevent the possibility of a switch being operated after an approaching train has accepted a proceed signal governing over the switch, and detector locking prevents the operation of the switch while a train is passing over it.

One of the outstanding features of the dispatcher-controlled system is that instructions are not relayed or dependent upon memory for their delivery. Neither are they subject to deficiencies in memory of the persons executing the orders. Instead, trains receive their orders by signal indication, displayed at the point where action is required. Furthermore, meets between trains on a single track are greatly facilitated, a large percentage of them being non-stop meets.

### TREND IN ART OF RAILWAY SIGNALING

Specifications for the complete installation of the various signal and interlocking systems and requisites covering the control circuits are published in the Manual of Recommended Practise of the Signal Section of the American Railway Association. The rules governing the operation of signals and trains under these systems are contained in the Standard Code of the American Railway Association.

The railroads are profiting, not only in reduced first cost but also through better performance, by the use of the modern standardized devices and control systems which have been developed through the work of the Signal Section and its predecessor, the Railway Signal Association, with the cooperation of the manufacturers of signal appliances.

Efficient transportation is largely dependent upon an efficient direction of train movements. The developments in the art of railway signaling, based upon the fundamental track circuit, have proved that directing train movements by signal indications is both practical and efficient. Abundant experience in every case has shown substantial economic advantages, an increase in safety, a reduction in train delays, an increase in ton miles per train hour and a decrease in total ton-mile cost.

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## Discussion

For discussion of this paper see page 313.

# Modern Signaling on the Reading Railroad

BY E. W. REICH* and G. I. WRIGHT†
Non-member Member, A.I.E.E.

***Synopsis.**—A description of one railroad's signal system limits most of the detail to the type of signals and interlockings standard on that particular road, however, there are many features of interlocking and signal control that are common to most modern signal systems. These features are described briefly in the paper.*

*Following a brief description of the earliest forms of signaling employed on The Reading Railroad, this paper describes the Reading's most recent installation of 100 cycle alternating current color light signaling.*

*The 100 cycle frequency was first used in the continuous coded train control territory, where a distinctive frequency was required to eliminate any possibility of foreign inductive interference, and was later adopted for use in electrified territory, as the range between the 100-cycle signal frequency and the 25-cycle electrification frequency permitted the use of frequency selective track relays.*

*The main features of the Reading's loop and code systems of continuous automatic train control and those of the automatic signaling and power interlockings are described in this paper.*

THE Philadelphia and Reading Railroad (now Reading Company) was one of the pioneer roads in the installation of automatic signaling and interlockings. The first form of signaling used was a manually-operated three-sided revolving tower, mounted on top of a raised signal cabin. The sides or faces of the signal towers were rectangular in shape, approximately four feet high and three feet wide, and were painted red, yellow or green for the day indication, with colored lights for the night indication. These signal towers were used to protect train movement on curves and were located on the side of track from which the best possible approach view could be obtained. When a train passed the signal, the towerman would turn the tower so as to display the red or stop indication and after a period of five minutes would turn it to the caution indication, following another period of five minutes he would place the signal in the clear position. This form of protection was, of course, very unreliable, as the towerman had no means of determining how far a train had actually advanced beyond the tower.

The first interlocking installation by the Reading Railroad on record is of a mechanical machine that was installed at Wayne Junction in 1880. This was followed by other installations of a similar type at most of the important junction and switching points. Operating officers were quick to recognize the advantage of controlling the position of switches and signals from a central point and the policy adopted by the Philadelphia & Reading Road placed it in a position along with other progressive roads to further the development of improved types of interlockings. This is best illustrated by noting that the Wayne Junction plant has had four complete replacements of the interlocking machine since the original installation. A mechanical plant served from 1880 to 1901; at this time a low pressure air machine with pneumatic operated switches was installed. Air for the switches was directly controlled by valves in the machine, including an air-operated indication device on the machine which indicated following the complete movement of switch points. The low pressure air plant required a multiplicity of small pipes radiating from machine to operated units and never proved very practical.

Following the installation of the low pressure air machines, rapid strides were made in the development of more practical power-operated interlockings. In 1911 the existing machine was replaced with an all-electric interlocking machine which was in turn replaced in 1929 by an improved type of all-electric machine. The last change was made in connection with the Reading's suburban electrification program.

Automatic signals were first installed on a portion of the Reading's main line in 1895, the signals were of the Hall disk type, which type of signal was standard until 1902 when the first two arm (home and distant) semaphore signals were installed. Following the advent of semaphore signaling the road's standard was changed to a single arm three position upper quadrant semaphore with marker light. This type of signal was in use until 1924 when the Reading, following experimental tests with various types of light signals, adopted the color light signal as standard.

As the most recent signaling installation on the Reading is located within its suburban electrified area, we shall confine our description to this territory.

*Power Supply and Distribution.* The development of automatic train control and frequency selective track relays now commonly used in a-c electrified territories made necessary that signal frequencies be distinctive and free from the inductive effects of other a-c systems. To meet this condition a 100-cycle signal frequency is used, requiring converter sets at signal substations, where the supply frequency is converted to 100 cycles.

Electrical energy for the operation of automatic signals and interlockings is distributed at 4,400 volts from ten signal substations located approximately twenty miles apart. Signal power is normally supplied from five of the stations; the remaining stations are located at the opposite end of each normal feed power section, automatically controlled so as to take the signal load in the event of a failure of the normal supply.

Throughout all of the terminal territory the signal circuits are carried in a concrete encased fiber duct line

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using two-conductor No. 2 or No. 4 lead-covered cable. In the outlying territory, signal lines are run in open wire on a wood pole line or on catenary structures.

Signal substations are located as follows:

| Location | Kva |
|---|---|
| Reading Terminal | |
| 60-cycle Reading Company supply | 120 |
| Wayne Junction | |
| 60-cycle Philadelphia Electric Company | 2–120 |
| Neshaminy Falls | |
| 60-cycle Philadelphia Electric Company | 120 |
| Yardley | |
| 60-cycle Philadelphia Electric Company | 30 |
| Chestnut Hill | |
| 25-cycle electrification circuit | 60 |
| 16th Street Junction | |
| 60-cycle Reading Company supply | 50 |
| Norristown | |
| 25-cycle electrification circuit | 75 |
| Nicetown | |
| 60-cycle Reading Company supply | 10–50 |
| Gladwyn | |
| 60-cycle Philadelphia Electric Company | 10–50 |
| Jenkintown | |
| 60-cycle Philadelphia Electric Company | 60 |
| Hatboro | |
| 60-cycle Philadelphia Electric Company | 50 |
| Lansdale | |
| 25-cycle electrification circuit | 75 |

All signal substations are non-attended except the Wayne Junction station where four signal lines radiating from this point are energized from a 100-cycle bus. The standby or reserve sets are started automatically and closed in on the line when machine voltage builds up to normal. Each station is controlled over a line relay which prevents it from closing on the line when the other station is feeding.

All frequency changer sets are provided with thermal protection on the motor and the generator has a full complement of under-voltage and over-voltage relays checking performance; outgoing 100-cycle feed is protected with a manual reset overload relay.

At Wayne Junction where there is parallel operation of two 120-kva frequency changer sets feeding a 100-cycle bus, the use of induction type motors necessitates special provision for synchronizing.

During part of the day it is possible to carry the load with one machine, but at peak load periods the second machine must be operated. At the time this second machine is closed in on the bus the first machine is operating at nearly full load, its frequency being synchronous less the slip frequency. To compensate for the difference between the frequency of the loaded and the incoming machines, an arrangement is used whereby a phantom load is placed on the incoming machine. This provides control of the incoming machine, regulating its speed to approximately that of the operating machine. The control circuits are arranged to drop the phantom load automatically when the second machine is connected to the bus. A current-compensating circuit operating on the machine voltage regulators insures an equal division of the wattless current. The division of power current is, of course, determined by the speed of the respective machines. The slip curves of the above machines coincide very closely and the power current of the two machines is equal under all load conditions.

The exacting voltage regulation required on signal lines makes it prohibitive to have an instantaneous drop in voltage when dropping one machine from the bus. To overcome this a circuit arrangement eliminates the current compensation and over-excites the machine that will remain on the bus. With this arrangement there is no noticeable drop in signal voltage in placing a machine on or off the bus.

Transformers are 4,400/110-volt, oil-cooled, of capacities varying from ¼ to 15 kva. No grounding is permitted of either the primary or secondary transmission systems, thereby isolating the signal circuit from the effects of other grounded systems. At transformer locations in open-wire territory both lines of 4,400-volt circuit are protected by lightning arresters. A separate earth connection is run to the transformer shell.

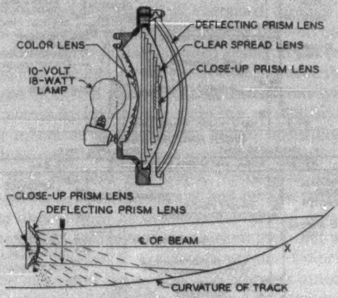


FIG. 1—LENS ARRANGEMENT AND METHOD OF FOCUSING OF A LIGHT SIGNAL

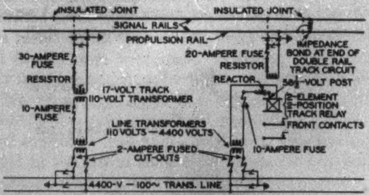
Solid lines represent beam spread of clear lens
Broken lines represent beam spread of deflecting lens
Dotted lines represent concentrated light beam for close-up view

Lighting for all the smaller stations in the electrified territory is taken off the 4,400-volt 100-cycle signal line. Where a station lighting and signal connection is required at the same location a double secondary transformer is used, thus permitting use of a grounded secondary lighting circuit without introducing grounds in the signal circuit.

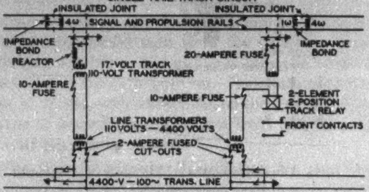
*Signals.* The modern signals are all of the long range color light type arranged with two or three light units; light signal cases are ventilated, and the entire lamp unit and case is assembled so that the lamp filament is in the exact focal point of the lens system. Accurate alignment is procured in the field by the use of a portable sighting telescope. On tangent track the signals are focused for a long range indication. On curves the signal is focused to the far point of the curve where the indication should first be picked up by the engineman. Continuous indication for approach on curves is provided by using a

10- or 20-deg deflecting prism or spread lens in which light rays are deflected in a horizontal plane toward the arc of the curve.

The lamp unit consists of a doublet lens with outer lens clear and inner lens colored. The lamp receptacle is supported in fixed relationship to the lenses. Thus, lamps are interchangeable. In addition to the doublet lens each unit has a small deflecting lens held in position by a spiral spring, immediately back of the center of the front or clear lens. This lens is commonly called a close-up prism and provides an intense color display in the center of the signal front lens, when the train is stopped immediately under or opposite a signal. Lamps used are of the double filament type rated at 10 volts, 18 watts. These are lighted at 9½ volts (slightly less than lamp rating) to insure a long burning life.


INSULATED JOINT
INSULATED JOINT
SIGNAL RAILS
PROPULSION RAIL
30-AMPERE FUSE
RESISTOR
20-AMPERE FUSE
RESISTOR
IMPEDANCE BOND AT END OF DOUBLE RAIL TRACK CIRCUIT
REACTOR
58½-VOLT POST
17-VOLT TRACK
110-VOLT TRANSFORMER
10-AMPERE FUSE
2-ELEMENT 2-POSITION TRACK RELAY
FRONT CONTACTS
LINE TRANSFORMERS 110 VOLTS — 4400 VOLTS
2-AMPERE FUSED CUT-OUTS
10-AMPERE FUSE
4400-V — 100~ TRANS. LINE

SINGLE RAIL TRACK CIRCUIT


INSULATED JOINT
INSULATED JOINT
4ω
SIGNAL AND PROPULSION RAILS
1ω
4ω
IMPEDANCE BOND
REACTOR
20-AMPERE FUSE
IMPEDANCE BOND
17-VOLT TRACK
110-VOLT TRANSFORMER
10-AMPERE FUSE
10-AMPERE FUSE
2-ELEMENT 2-POSITION TRACK RELAY
FRONT CONTACTS
LINE TRANSFORMERS 110 VOLTS — 4400 VOLTS
2-AMPERE FUSED CUT-OUTS
4400-V — 100~ TRANS. LINE

DOUBLE RAIL TRACK CIRCUIT

FIG. 2—TYPICAL SINGLE AND DOUBLE RAIL TRACK CIRCUIT

Signals are located on masts to the right of, or on catenary structures immediately over the right rail of the track governed. Where signals are mounted on catenary structures they are located 21 ft above top of rail. Ground masts are located to the right of track governed, with near side of mast 10 ft from the center line of track. Signal units of interlocking signals are arranged as follows:

*Two-unit Signal.* Center of red lens of bottom or slow-speed unit 10 ft above top of the rail with 12 ft spacing to center of red lens in top unit.

*Three-unit Signal.* Center of red lens of bottom or slow-speed unit 10 ft above top of rail with 7 ft spacing to middle and 5 ft middle to top unit.

*Automatic Signal.* Center of red lens of marker light or third block indication unit 10 ft above top of rail and 7 ft between red lens of marker and automatic signal unit.

*Aspects and Indications.*

Interlocking Signals

| Rule | Aspect | Name |
|---|---|---|
| | | Interlocking Signals |
| 601A | Red-Red-Red<br>Red Red<br>(dwarf) Purple | Stop<br>(Route is not set) |
| 601B | Yellow-Red-Red<br>Yellow Red | Approach<br>(Prepare to stop at next signal. Train exceeding medium speed must at once reduce to that speed) |
| 601C | Green-Red-Red<br>Green Red | Clear<br>(Proceed at time-table speed) |
| 601D | Red-Yellow-Red | Medium Approach<br>(Proceed at not exceeding medium speed prepared to stop at next signal) |
| 601E | Yellow-Green-Red | Approach medium<br>(Approach next signal at not exceeding medium speed) |
| 601F | Red-Green-Red | Clear medium<br>(Proceed at not exceeding medium speed) |
| 601G | Red-Red-Yellow<br>Red Yellow<br>(dwarf) Yellow | Restricting<br>(Proceed at restricted speed) |
| | | Automatic Signals |
| 501AA | Red-Red | Stop and proceed<br>(Stop then proceed block is not clear) |
| 501B | Yellow-Red | Approach<br>(Prepare to stop at next signal. Train exceeding medium speed must at once reduce to that speed) |
| 501C | Green-Red | Clear<br>(Proceed) |
| 501E | Yellow-Green | Approach medium<br>(Approach next signal at not exceeding medium speed) |

*Automatic Signals.* In general the automatic signaling is of the three indication—two-block type, however, at approaches to interlockings where a restricted route signal may be displayed or where the spacing between automatics does not provide sufficient braking distance four indication—three-block signaling is installed.

Existing installations made prior to electrification had both polarized line or clearing and track relays. In electrified territory where track circuits are limited to the use of two-position frequency track relays, recent installations have been made with neutral line control. This form of control is adaptable for future extension of cab signal territory.

Line control circuits are normally energized, but the signals are lighted only during the time a train is in the approach block to the signal and until the block beyond the signal is cleared. Where more than one track is signaled in the same direction, signals for both tracks at the same location are lighted by the approach of a train on any one track.

Automatic signal control provides that a stop indication be displayed when

Train, engine or car is in the block immediately in advance of the signal.

Any switch or derail in block is reversed or switch points not fully closed in their normal position. A switch point tolerance of less than ¼ in. is permitted.

A rail is broken, interrupting track circuit.

Cars extend beyond the fouling point on sidings.

*Interlockings.* Electropneumatic interlocking plants are installed throughout most of the terminal territory where frequency and speed of operation is an important factor. However, power interlockings are not all of the electropneumatic type. There are a number of all-electric plants in service. Interlocking circuits provide a standard arrangement of approach, sectional, route and detector locking.

*Approach Locking.* This is an arrangement of electrical control which permits changing signal from the proceed to the stop indication, but acts to prevent any change of route in advance of an approaching train. A release is provided in the approach locking circuit through the medium of a clockwork time release set for two-minute operation. Circuits are arranged so that time delay must follow the change of signal from proceed to the stop indication.

*Sectional Route Locking.* Sectional route locking provides for the electrical control of detector locks on switch levers throughout an entire interlocking route. When the interlocking signal is cleared for an approaching train, all switch and opposing signal levers are locked mechanically in the machine. The electrical route locking becomes effective when a train passes the signal governing movement through the interlocking.

*Detector Locking.* Detector locking is the electrical control to the normal and reverse locks of switch levers which acts to prevent movement of switches located within the limits of a track circuit in which a train is located or within a section of route locking in advance of the train.

*Track Circuits.* The operation of approach, route and detector locking in interlockings and the control of both interlocked and automatic signals is all based on the signal track circuit. Track circuit limits are defined by insulated joints placed in the track rails. At one end of the circuit current is fed to both rails of the track from a 300-volt-ampere transformer with variable secondary voltages. At the other end a relay is energized from rail connections. When a train enters the circuit, track current passes through the wheels of the rolling equipment short-circuiting the normal current path and deenergizing the relay. The deenergizing of the track relay opens the front and closes the back contacts over which signal circuits are controlled. All of the track relays used in electrified territory are of the centrifugal frequency type which are selective between the 25-cycle propulsion current and the 100-cycle signal frequency. These track circuits are divided into single and double rail types. The double-rail circuit is used in automatic signal territory and requires a double coil impedance bond at each end of the circuit, to provide a return for the propulsion current. Single-rail track circuits are used in interlockings where the control of route and detector locking requires that each signal block be divided into a number of short track sections.

In the single-rail track circuit one of the rails is bonded straight through for propulsion current, the other rail is equipped with insulated track joints to define track circuit limits.

The use of single rail circuits results in a saving in installation costs, as the only impedance bonds required are where the single-rail track circuits adjoin the double-rail type of the approach or receding track circuits to the interlocking. Double-rail track circuits vary in length,where drainage and ballast conditions are favorable, a maximum length of 5,000 ft is permitted. The length of single-rail track circuits is limited to 1,200 ft so as to provide for broken rail protection.

*Switch Operation.* Power-operated switches whether of the all-electric or electropneumatic type are controlled directly from rotary circuit controllers mechanically connected to levers of the interlocking machine. This control (usually 110-volt a-c) actuates a polarized controller at the switch for all-electric movements or an arrangement of *Z* armature electropneumatic valves on the air plants. Actual switch operation is thereby controlled locally at the switch. In the electric movement the switch operating circuit is energized through contacts on a polarized controller from the 100-volt mains. In the same manner air is controlled locally at the switch from the main air line for the pneumatic movements. In each type of switch movement, motion is conveyed to switch points by means of a slide bar carried on anti-friction rollers or guides to the switch operating rod through an open throat jaw or escapement crank.

The slide bar also provides a mechanical lock for switch points in both the normal and reverse positions. Locking dogs riveted to the slide bar are so arranged that they enter a narrow slot in switch lock rod, which is directly connected to the switch points. Coincident with the locking of the switch, the power is automatically disconnected from the operating mechanism and switch points held in position by the mechanical lock. A switch point tolerance of not more than 3/16 in. is permitted in the adjustment of this mechanical lock.

Having provided an operating control and a mechanical lock for switch movements, it is clear that a check should be made to insure that the switch has followed the movement of the control lever in the interlocking machine and that the switch is mechanically locked. This is accomplished by controlling the electromagnetic switch indication lock through a three-position switch repeating relay. This lock acts to prevent placing the switch lever in full normal or reverse position until the switch has completed full movement of points and is mechanically locked. The indication circuit is a polarized control of a three-position, two-element vane type relay, in which controller mounted on and actuated by movement of slide bar in the switch mechanism acts as a pole changer to the control element of the switch indication relay. This polarized control energizes the relay in a predetermined position when the switch is normal and to the opposite position when the switch is reversed. Circuits on the controller are so arranged that control wires to the switch repeating relay are shunted during the time that the switch is in transit. This same polarized switch repeating relay is used to control the clear position of signals routing through the plant.

Switch operation may be summarized as follows: First movement of slide bar unlocks the mechanical connection to the switch points and opens control of switch indication circuit, continued movement of slide bar actuates the switch points, the final movement of bar locks switch in the opposite position and closes indication circuit.

*Lightout Protection.* The lighting of signals is controlled over relay contacts with lighting circuit energized by a special 110/10-volt lighting transformer located in a relay housing adjacent to the signal. A special circuit was developed to check against a burnout of the lamp filament. The circuit arrangement provides a rectifier-controlled d-c relay in series with the lamp lighting and lamp filament circuit. Through this scheme of control it is possible to indicate the actual lighting or failure of a signal lamp by the medium of repeater lights in the tower.

Lightout circuits provide for the following features:

Automatic transfer of lighting circuit from an approach or clear indication to stop, in the event of a burnout when approach or clear is displayed; information is repeated to towerman who can then clear slow-speed signal for the route.

Checks that red lamp is lighted on normal route signal before proceed or approach indication can be displayed in restricted route signal. Under this circumstance the slow-speed signal may be cleared.

Checks that all red lamps are burning when signal lever is placed in normal or stop position, by controlling the approach locking circuits over lightout relays.

*Model Board.* Manipulation charts are provided in each interlocking tower indicating the proper sequence of switch and signal lever operation for the various routes. In addition to this chart, an illuminated model board is provided on which a complete track diagram indicates the location of switches, signals, track circuits within and the approach circuits to the interlocking. Track circuit limits on model board are defined by colored sections of track including a miniature light in each section which is illuminated when that particular track section is unoccupied. Model board lights also repeat the stop and clear signal indications of the interlocked signals and in addition, the indication displayed at distant signals approaching the interlocking.

With this arrangement the towerman can follow the movement of each train from the time it enters the approach section until the interlocking proper is cleared and it makes possible the control of two or more interlockings from a central point.

A summary of interlocking control in the sequence that it occurs follows:

1. The approach indicator and annunciator bell indicates the approach of a train.
2. Route is set by means of power-operated switches with repeater lights and electric locks indicating track circuit conditions and checking switch operation.
3. Signal is cleared, mechanically locking all switches and opposing signals in route, approach electric locking becomes effective, indication of interlocking home and the distant signal is repeated in the tower.
4. Train passes interlocked signal releasing approach locking, signal lever may now be returned to stop position, sectional route and detector locking becoming effective.
5. Release of route and detector locking in the rear of a passing train permitting a change in route for another move.

*Train Control—Loop System.* The first installation of train control was made in 1925 on the Atlantic City Railroad covering a territory of 55 miles between Camden and Atlantic City. The system installed is a continuous speed control with speeds of 85, 40 and 25 miles per hour imposed, together with a three-indication cab signal indicating high, medium or low speed. High speed or 85 miles per hour which is maximum permissive speed on this branch is imposed in clear blocks, medium speed of 40 miles per hour between a caution signal and braking point in approach of a stop signal and low or 25 miles per hour between this braking point and the stop signal and while passing through an occupied block.

In this system there is a two-element train-control relay located on the locomotive, the track element being energized through what is known as an axle circuit. The secondary of the track transformer is connected across the rails at the receding end of track circuit, current flows through one rail toward train in circuit across wheels and axle of locomotive to opposite rail, thereby completing the circuit. The flow of this current in the rails induces a second current in a receiver on the front end of the locomotive mounted a few inches over the rails, this current is then passed through special power amplifier tubes and then to one element of train control relay. The other element receives energy from a combination line and track circuit known as the loop circuit.

This loop circuit requires a special transformer connected through resistance coils to both rails of the track circuit, and the circuit is completed through a line wire running the entire length of the block which is connected to both rails of the track circuit at the opposite end. Current flowing in the loop circuit (through both rails in parallel and line return) is picked up by a second receiver mounted on the rear of the locomotive and through amplifiers energizes the local coils of the train control relay.

The three-position train control relay assumes a vertical position when either or both of its control elements are deenergized, and is energized in a predetermined position when both elements have a current flow with a certain phase relation, and energized in the opposite position when current in one of the elements is reversed. This change of phase relation is accomplished through the pole changing of the line or loop circuit as the polarity of track elements is always constant. The polarity of loop circuit is controlled through the position of wayside signal controlled two blocks in advance of the one occupied, thereby coordinating train control and cab signaling with the wayside signal indication. The electropneumatic brake equipment and cab signals on the locomotive are actuated by local circuits controlled by the train control relay above described. The current for operating this local equipment is supplied from a special generator which also serves to furnish power for the electric headlight of the locomotive.

*Train Control—Continuous Code Type.* The second installation of train control was made on the Bethlehem Branch in 1927, extending from Jenkintown to Bethlehem, a distance of 46 route miles.

The system installed is a continuous two-speed code type with four-indication cab signaling, a low speed of 20 miles per hour being imposed under certain track or block conditions. Unlike the loop system of train control previously described, where the train control relay was actuated from a combination of track and line circuits, the code system depends entirely on track or axle current. Code energy flows in one rail of track to the front wheels and axle of the locomotive returning to the transformer through the other rail. This flow of axle current induces a second current in receiver coils mounted on the locomotive ahead of the front wheels. The two receiver coils are electrically connected so that the voltages induced in them are additive when alternating current flows in opposite directions in the two rails. The circuit of receiver coils is tuned to resonance at 100-cycles and induced current passes through two stages of transformer coupled amplification to a master transformer and relay, which in turn actuates the several decoding relays tuned to a code frequency for the various cab signal indications and the pneumatic brake control.

Code is obtained from a small motor-operated coder through which the various code frequencies are superimposed on the track circuit coordinated with the position of wayside signal equipment for two blocks in advance of the one occupied.

Control codes are as follows:

| Frequency | Indication |
|---|---|
| 180 | Clear |
| 120 | Approach medium and imposed slow speed |
| 80 | Approach and imposed slow speed |
| 0 | Stop with imposed slow speed |

It is characteristic of both the loop and code system of continuous train control that any change in conditions occurring at any time in the clear block immediately causes a change to a more restrictive signal in the cab or locomotive and functions to initiate an automatic application of the brakes. Conversely, cab indication and control of automatic brake equipment is released immediately following any change in conditions ahead, which would make a higher speed permissible.

The arrangement of pneumatic brake control necessitates that the engineman operate an acknowledging lever when a change to a more restrictive indication occurs. The engineman then has a six-second interval to initiate a reduction to the imposed speed that is permitted with the particular cab indication being displayed. Unless the engineman immediately acts to acknowledge and reduce speed, train control equipment will function and stop the train. With this form of pneumatic control it is impossible for an engineman to observe a restrictive indication at wayside signal in advance of the train, forestall the application of brakes and proceed at an unauthorized speed.

## Discussion

For discussion of this paper see page 313.

# Centralized Traffic Control and Train Control
## of the Baltimore and Ohio Railroad

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and
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Non-member

***Synopsis.**—This paper describes the facilities provided for centralized traffic control and gives detailed information with respect to two installations on the B. & O. Railroad. The operation of an intermittent inductive auto-manual train stop system on the B. & O. Railroad is also discussed.*

* * * * *

### CENTRALIZED TRAFFIC CONTROL

*Purpose of System.* The purpose of a centralized traffic control system is to concentrate at one point under the direction of one operator the control of train movements over a long section of track, and to expedite the movement of traffic in that section. This is accomplished by bringing within view of the operator, indications as to the location of trains and the position of all switches and controlled signals, and also by bringing within his reach means whereby he is enabled to change, when safe to do so, the position of switches and signals affecting the movement of trains.

*Devices Employed.* A centralized traffic control system incorporates practically all of the devices and appliances ordinarily installed in a low-voltage interlocking system and a complete single-track automatic block system. Rails are bonded, insulated and otherwise equipped to provide complete track circuit protection. Hand-operated switches are equipped with switch circuit controllers which if opened more than one-fourth inch, prevent the display of a signal indication more favorable than "stop," or "stop and proceed." Dual control switch machines, *i. e.*, switches that may be operated either by motor under the control of operator or by hand at his direction, are used at the entrance and exits of passing sidings, junctions and ends of double track. The normally open hand-operated derails located on commercial sidings near the fouling of main track, are equipped with switch circuit controllers, through which the signals governing main track movements are wired. Relays perform the usual duties in the operation of the system, and in addition are wired to provide local protection in the field in lieu of route and detector locking. They are also extensively used in combination with the transmission system. Line conductors for the block signal, indication, and coding circuits are carried in aerial cables.

Color position light signals—standard under all methods of signaling on The Baltimore and Ohio Railroad—provide the indications which govern the movement of trains without the use of train orders. The signals consist of a cluster of lights, two red, two yellow and two green mounted either on a high mast in which case they are called high signals (Fig. 1), or on a lower support in which case they are called dwarf signals. Dwarf signals provide the same indications as high signals and are controlled in the same manner.

Red lights are displayed horizontally and when lighted indicate "stop." Yellow lights are displayed diagonally rising from left to right, and when lighted indicate "approach next signal prepared to stop." Green lights are displayed vertically and when lighted indicate that two or more blocks are clear.

These colored lights provide block protection for all routes, and are augmented by white markers to indicate which route is set. A white marker above the blocking lights indicates the route is set and the track alinement is such that a train may, if the block is clear, move at normal speed. A white marker below the blocking lights indicates the route is set and the alinement is such that a train may, if the block is clear, move at medium speed. The absence of a white marker above or below proceed blocking lights indicates that train movements must be made at slow speed.

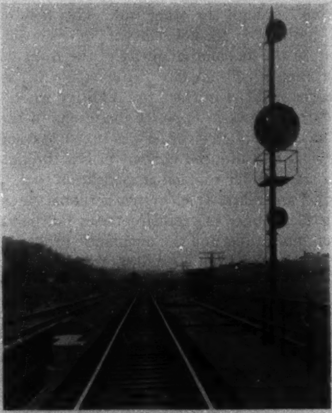

FIG. 1—HIGH SIGNAL GOVERNING OVER SWITCH AT A LAP SIDING

Signals located along single track sections between meeting points or junctions are automatic, and require no manipulation by the operator. Those located for the protection of motor-operated switches are semi-automatic and have triple control, namely:

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*Baltimore & Ohio Railroad Co., Baltimore, Md.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

1. Automatic control, that is, by track circuit.

2. Switch control. Switches must be in proper position in order to provide an indication more favorable than "stop."

3. Manual control. Operator must, through the manipulation of levers, give his consent.

*Controlling Machine.* Operation of the above mentioned signals and switches is accomplished by means of a controlling machine. This consists of a control panel mounted vertically above and extending across the back and along the two sides of a flat top desk in such a way that all points on the panel are within easy view and reach of the operator or dispatcher. A diagram along the top of the panel shows the arrangement of the tracks, switches and signals controlled by the machine. Occupancy of a section of track by a train is indicated by the lighting of a miniature lamp in that section of the diagram. Rotating levers or knobs for the control of switches and signals are located under the track diagram, each lever or knob being situated directly beneath its corresponding switch or signal. In the immediate vicinity of each switch lever or knob is located one or more lights which indicates the position of the switch, also near each signal lever or knob is one or more lights which indicates whether a "stop" or a "proceed" signal is being displayed.

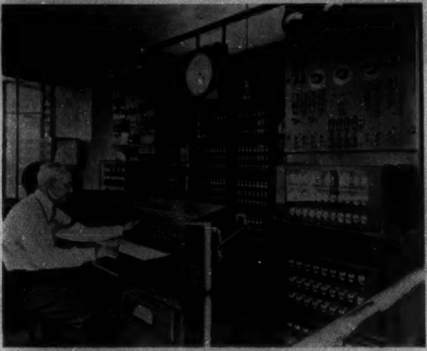

Fig. 2—Control Machine at West Washington, Pa.

On the flat surface of the desk in front of the control panel is an automatic train graph which provides an automatic time chart record of all train movements through the controlled territory. Fig. 2 is from a photograph of the control panel and other associated equipment which actuate the indicating devices, signals and switches.

*Communication System.* The system is similar to supervisory control and printing telegraph systems in that the control of function is transmitted through the medium of code. This system was designed to meet the requirements of railroads for centralized control of a large number of field stations of relatively few functions each. The field stations are spaced, non-uniformly, generally at each end of a passing track, at the ends of double track, and at other points where switches and signals are controlled.

Station equipment is designed:

To operate switches in either their normal or reversed positions.

To control signals in either their "stop" or "proceed" positions.

Field stations are controlled one at a time, on successive cycles of operation. Office codes transmitted to field station are started manually by the operator. In the event that controls are initiated to several different field stations in rapid succession, the controlling pulses will go to one station at a time, in a predetermined order, fixed at the time of installation. The miniature lights on the control panel show for each controlled station:

1. Switches normal or reversed.
2. "Stop" or "proceed" signals displayed.
3. Whether a train occupies the short section of track which includes the switch.
4. Whether a train occupies the track approaching the switch.

Field codes transmitted to the control office are started automatically by the energization or deenergization of the control relays. Field stations send in their indications, one station at a time on successive cycles, and in the event that several stations initiate indications simultaneously, they will act to transmit their indications one station at a time in a predetermined order, fixed at the time of installation. Field code equipments are identical and interchangeable in each individual system. Each station is, however, responsive only to its own code.

### Descriptions of Installations

Two major sections of single track centralized traffic control on The Baltimore and Ohio Railroad—one extending from Gilkeson, Pa., to Wheeling, W. Va., a distance of forty-three miles, and the other from North Lima to Roachton, Ohio, a distance of fifty-six miles;—were placed in service during the year 1931. Prior to these installations trains were dispatched by means of time-table, train orders and a manual block system. These methods became inadequate properly to care for the number of trains being operated and there were consequently excessive delays resulting in overtime. The principal delays were occasioned by:

1. The necessity for stopping trains when entering or leaving a siding, and for stopping or slowing down to receive train orders.

2. The enforcement of manual block rules which do

not permit another train to enter a block occupied by a passenger train.

3. Inability of trains to make their meeting or passing points at the time calculated by the dispatcher, due to causes beyond his control.

These delays made it necessary to provide additional track capacity either through the medium of double tracking or through the installation of centralized traffic control. A comparison of the estimated cost of the two mediums resulted in the conclusion to install the C.T.C. system.

### GILKESON, PA., TO WHEELING, W. VA.

A system known as the G-R-S Duplex Centralized Traffic Control is now in service between Gilkeson, Pa., and Wheeling, W. Va.

The control machine is situated in the second-story of a fire-proof tower located at West Washington, Pa. The installation includes the operation of switches, at eleven passing tracks and at the end of a double track, as well as the signals at these locations. A total of 23 power-operated switches, 70 controlled signals, and 38 automatic block signals is involved in the project.

As its name implies, this system provides for the simultaneous transmission of controls to, and the receipt of indications from, the same or different field stations. Two circuits extend from the control tower to the ends of the C.T.C. territory, one for outgoing control, the other for incoming indications. The system is normally at rest and is automatically set into operation whenever the operator uses the control machine, or by a change in field conditions requiring the transmission of a new indication. During the first portion of the cycle, when the system is set into operation, a particular combination of positive and negative impulses on successive steps, select the field station being called by the operator to receive new controls, or if a field station is in control of the transmission it will either open or leave closed the indication circuit on the succesive steps to register its identity in the control office. Any one of 128 different stations may be thus selected or registered on the seven station selecting steps. After the selection or registration of a field station, the eighth step conditions the system for the next part of the cycle, comprising the last eight steps, which is used for transmitting controls or receiving indications.

The movement of a switch lever does not start a code if moved alone, but the code is initiated by the movement of a signal lever to the left or right or by operation of its associated starting button. To line up a route the dispatcher operates the proper switch levers and signal levers. This starts the operation of the relays comprising the code system. The first set of impulses select the proper field station and the following impulses cause the proper action of the signal apparatus at the selected field station.

### NORTH LIMA, OHIO TO ROACHTON, OHIO

The installation between North Lima, Ohio and Roachton, Ohio is known as the U.S. & S. Co. Three Wire Circuit Code Scheme. The three line wires comprising two normally closed circuits with a common return, are of No. 12 gage in cable.

The control machine is situated in the second-story of a fire-proof tower at Deshler, Ohio, Fig. 3. The installation includes the operation of 34 motor-operated switches such as shown in Fig. 4, 88 controlled signals, and 34 automatic block signals. There is no interconnection between code circuits extending north and those extending south of the control office. Each circuit includes one relay in each field station and office, all in series. A circuit code is used, no time interval being employed except at the completion of a code.

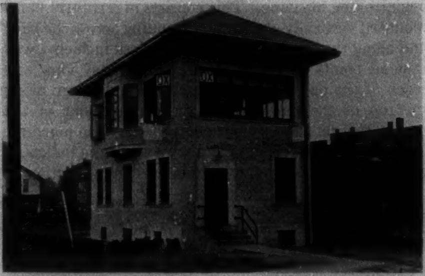

FIG. 3—TOWER AT DESHLER, OHIO

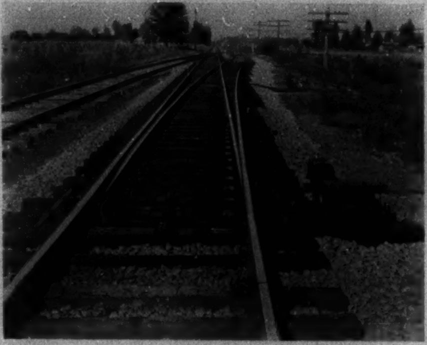

FIG. 4—POWER-OPERATED SWITCH, CONTROLLED FROM DESHLER, OHIO

There are eight open circuit steps which may be generated at the office or at any station by counting chains of fifteen relays. Any of the eight open circuit steps may involve the opening of the first circuit only, the second circuit only, or both circuits, that is, three circuit conditions. The first step is primarily to differentiate between office and field-initiated codes and to lock out others, the office codes always starting with both circuits open and the field codes with either single line open. The first step locks out and prevents code sending to all units except the one desired. If the office and a station start simultaneously, the office takes precedence. If two or more stations start at the same time, the one nearest the control office is completed first. The locked out stations are held back and function in their proper turn.

Office codes are started manually while field codes are automatically started, by disagreement circuits, closed whenever any indicated function undergoes a change. Four steps are allocated to station selection, and eighty-one different selections are possible. Three steps are for operating and indicating functions. The code of eight steps requires approximately 1.5 seconds or 0.1 second for each counting relay, and it is interesting to note that about ninety-five total relay operations per code take place at each station. This short code period is necessary in large installations because there are times when a considerable number of codes must be transmitted in a brief space of time and delay is often not tolerable.

Due to these requirements of reliability and high speed, it was necessary to take care of variations in temperature, local battery voltages and relay adjustments, and to require positive registering of each step at all receiving stations before completing the step, the time duration of a code being that of the slowest code equipment. If a station fails to respond with reasonable promptness it is dropped out, permitting all others to function.

## Summary

The systems operate as intended.

Train delays incident to the opening and closing of passing siding switches or stopping or slowing down for train orders have been largely eliminated.

Expenditures for operating labor, overtime and fuel have been reduced.

Track capacity is greater due to the closer spacing maintained between following trains, and safety of operation has been increased.

## Intermittent Inductive Auto-Manual Train Stop System

In 1922, the Interstate Commerce Commission issued an order to 49 Class 1 Railroads requiring each of these roads to make an installation of automatic train control on a full passenger locomotive division by January 1, 1925. In January, 1923, the Commission issued an extension to this order whereby 47 of the original 49 roads were required to install train control on a second division and 45 additional roads were required to install control on one division, thus involving a total of 94 roads and 141 passenger locomotive divisions.

As The Baltimore and Ohio Railroad was affected by the Commission's order to the extent of two divisions, it became necessary to investigate the principal systems offered at this time and select the one best adapted to its requirements. The territory first proposed and later approved by the Commission was from Baltimore, Md., to Washington, D. C. Although the distance between these two cities is only 34.6 miles, yet due to the very heavy passenger traffic, it was thought that this territory would offer a severe and thorough test in performance and capacity for any system.

It was essential that a system should be chosen which would not only meet the Commission's requirements, but one which would not reduce the capacity of the line. After much detail study recommendation was made that the General Railway Signal Company's "intermittent inductive auto-manual train stop system" be installed, not only between Baltimore and Washington but also between Baltimore, Md., and Philadelphia, Pa., a distance of 92.5 miles to meet the requirements in the second order of the Commission.

## Description of the System

This train stop system is superimposed on the automatic block signal system.

The block signal system makes use of the track rails in combination with relays and insulated joints dividing the trackway into blocks. A potential is impressed across the rails at the leaving end of the block, the rails being bonded into a conductivity continuous circuit to the entering end. A translating device such as a relay responding to low potentials is located at the entering end, and controls the indications of a wayside signal installed at that point. When the track rails are continuous and the trackway is unoccupied, the relay at the entering end of the block will be energized, thus transmitting such indication to the wayside signal, permitting an oncoming train to run with unlimited speed in so far as occupancy of the particular track is concerned. By overlapping the control, the signal indicates the condition of two successive blocks. Thus if the two blocks ahead are clear the signal will show the indication "proceed with speed," while if only one block in advance is clear, the indication displayed is "prepare to stop at the next signal." This indication is usually termed the caution one. When the block immediately beyond a given wayside signal is occupied or its rails are broken or other hazardous conditions obtain therein, the signal at that location displays "stop and proceed, prepared to stop on vision." The observance of these restrictive wayside signal indications is enforced by means of the auto-manual train stop system.

The auto-manual train stop system consists of two distinct parts: the locomotive equipment, and the wayside equipment. The wayside equipment is a device known as an inductor, which is located approximately

70 feet in front of each block signal governing the entrance to a block in the direction from which the signal is approached and is placed just outside the right-hand rail. Although this inductor is electrically connected to its signal by two insulated wires, it normally carries no current. It consists of a U-shaped magnet with laminated cores, large pole pieces, and a coil which is connected to the front contacts of the signal control relay located at the base of the wayside block signal.

FIG. 5—LOCOMOTIVE RECEIVER OVER WAYSIDE INDUCTOR

The locomotive equipment consists of a receiver, a group of relays, electropneumatic valve, an actuator, a forestalling device, and a reset contactor. The receiver is mounted on the right side of the forward tender truck of the locomotive in such a location as to pass two inches above and directly over the inductor. There is no physical contact between the two. This device is an inverted U-shaped magnet with laminated cores and large pole pieces. It carries two coils, which are called the primary and secondary coils. Its general appearance is shown in Fig. 5.

The relay group is contained in a spring-mounted housing located on the deck of the tender tank. Its functions will be described later. The electropneumatic valve is located in the cab. It takes energy from the relay group and controls the brake-valve actuator. A brake-valve actuator is used to rotate the engineman's brake valve to the service position when an automatic application of the brakes is made. An acknowledging contactor located in the cab is used to forestall an automatic brake application by manually operating its handle. A reset contactor is located on the side of the tender and is operated from the ground after the train has been brought to a complete stop.

### OPERATION OF THE SYSTEM

As the locomotive passes a wayside signal which is displaying a "caution" or a "stop" indication, its receiver passes over the inductor on open circuit, (see Fig. 6). A surge of magnetic flux builds up in the secondary coil of the receiver and produces a momentary negative current in the relay. This negative current is sufficient to allow the relay to open, and when once open, stays open until restored, due to its being a "stick" relay. The opening of the primary relay deprives the electropneumatic valve of energy which causes the valve to open and release the air from the larger piston of the actuator. The actuator, therefore, moves the brake valve to the service position which applies the brakes to the moving train.

The system is so arranged that the engineman can at all times operate his brake valve to the service or emergency position, but he cannot release the brakes manually during an automatic application. To restore the system to normal and release the brakes after they have been applied by the system, it is necessary for him to leave his seat and operate the reset contactor.

If the engineman is alert and fully capable of handling his train, he can forestall a brake application when passing a "caution" or "stop" signal indication by operating an acknowledging contactor located within easy reach of him in the cab. Under this condition a whistle sounds when the receiver passes over the inductor; when the whistle stops, it indicates that the acknowledging lever should be restored to normal position. He must, however, release the handle in 15 seconds. If he held it for a longer period, the brakes would be applied automatically, but could be released after restoring acknowledging contactor to normal position.

When the train passes a wayside block signal which is displaying a "clear" indication, the coil of its inductor is on closed circuit. As a result, the receiver may pass over an inductor in the clear condition without a reduction of the primary relay's current intensity to the drop-away point. Therefore, the electropneumatic valve will remain energized and no brake application will be effected.

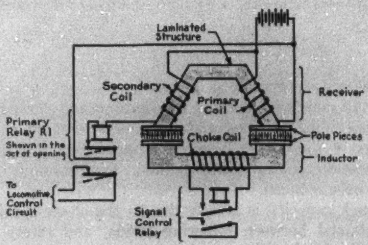

FIG. 6—CIRCUIT SHOWING PRINCIPLES OF CONTROL, WAYSIDE TO LOCOMOTIVE

### ACKNOWLEDGMENTS

Credit is given the General Railway Signal Company and the Union Switch & Signal Company for their cooperation in preparation of this paper.

# Discussion

## RAILROAD SIGNALING AND TRAIN CONTROL

(Amsden and Vandersluis)

## MODERN SIGNALING ON THE READING RAILROAD

(Reich and Wright)

## CENTRALIZED TRAFFIC CONTROL AND TRAIN CONTROL

(Davis and Dryden)

**W. A. Jackson:** No one seems to have thought to include anything of the history of the development of centralized traffic control, especially in view of the statement made that it was the most forward item of progress in railroad operation in 55 years.

About 20 years ago, soon after the development of the first selector for use on train dispatcher circuits, it occurred to one of the Telegraph Departments of the New York Central Lines that a selector could, in connection with the dispatcher's telephone circuit, be made to cause the operation of signals for various indications. I do not believe that any thought of operating track switches entered our minds at that time, but, of course, it must have been obvious later that if we could operate signals we could do most anything else. The first selector used was a Western Electric type which was called a telegraph selector. This was a good selector but the scheme had the serious fault that the same code of impulses that set up the signal, also cleared it, and the trouble was that the train dispatcher would occasionally forget that he had not cleared his signal and when he put it up for the following train the engineman would find the signal clear instead of set. It should be understood that there was no danger attached to this sort of operation as the only use for the signal operated by the dispatcher was to head a train in on a siding to let a following train pass, or to give him a passing record of the train by the location of the signal. The General Railway Signal Company became interested and developed a selector which was a splendid piece of apparatus and almost fool-proof. It had one fault, however, in that it depended on reversals of current and when the telephone line was patched in the case of trouble, or anything else happened that involved the changing of the wires, it upset the operation and the reversals of current were frequently, under such circumstances, of the opposite polarity of what they should be. Later, the Union Switch and Signal Company also became interested. However, it was not wholly a practicable arrangement for railroad operation until the development of the Western Electric so-called a-c selector, which is the same type as is used in remote control systems in the various lines of electrical power and communication work.

The writer thinks the centralized traffic control system was first placed in use between Berwick and Stanley Yard, near Toledo, along the Ohio Central Lines of the New York Central and that it was installed in 1927.

**R. M. Phinney:** Centralized traffic control, it is believed by many, is the first major development in the method of operation of trains since the introduction of the train order in 1851, over eighty years ago, and which it is now superseding on rapidly increasing mileage. There are now about 900 road miles of centralized traffic control in service, the first installation of which was made in 1927.

Among the many advantages of centralized traffic control there are two which, during this period of reduced traffic due to business conditions and the inroads being made by other means of transportation, can profitably be investigated as a source of immediate as well as continued economy:

1. The elimination of second and third track which was justified when built, but under present and in many cases future conditions, would not be required. There are many situations on multiple track lines where centralized traffic control can handle the traffic with one less track in service. The consequent saving in taxes and maintenance will amount in some cases to as much as $4,000 per main track mile per year.

In recent years there has been abandoned a large mileage of railway main line, for the most part branch lines, but a number of miles of second track has been included. The Irish railways lead the way by abandoning about 100 miles of second track.

2. The second item of economy that should be emphasized is the consolidation of interlocking plants. This merely needs to be mentioned as the economy is evident. This consolidation is continually going on but there are still many situations where efficiency of operation can greatly improve by consolidation.

**J. E. Saunders:** The papers demonstrate the similarity of the telegraph-telephone, and the railway signaling systems. The former covers the transmission of information by voice and telegraph; the latter principally by signs, color or position, through means of roadside and cab signals.

The primary purpose of railway signaling is safety. Its secondary purpose, which is that of providing a more economic transportation means, has come rapidly to the front during recent years. A pamphlet which will be published by the Signal Section, American Railway Association, in a few months will show the means of securing savings varying from 20 to 100 per cent per annum on the cost of making them effective, with typical specific examples where such savings have been demonstrated.

The paper presented by Messrs. Amsden and Vandersluis is of particular value to those who cover a wider field of electrical engineering in that it describes in a concise way the various ramifications of railway signaling and train control; that by Messrs. Reich and Wright, while applying specifically to the Reading Company, may be assumed as showing the general practise in more modern installations of signaling on electrified lines throughout the country. The paper by Messrs. Davis and Dryden covers in detail one of the more important and recent economic developments in railway signaling, centralized traffic control, as well as one of the systems of automatic train control.

It is interesting to know to what extent signal and interlocking practise on a railroad having direct current propulsion differs from one utilizing alternating current. These differences are given in the following and the points wherein the Lackawanna Railroad, New Jersey suburban electrification, deviates from the Reading, Philadelphia suburban electrification, which was put in at about the same time.

The Lackawanna power supply was 2,300 volts single-phase 60 cycles transmitted from substations which were so spaced as to make a higher voltage unnecessary. Since this frequency came from the primary source, frequency changers were unnecessary.

While the same type color light signal units were used, the Lackawanna system of simplified aspects permitted less units to be installed.

The track relays are of the inductive vane type and assume two positions, being energized when no train is on the track circuit and deenergized when there is a train. This compared with the a-c propulsion practise of using a centrifugal frequency relay which is running continuously during those periods when track circuits are unoccupied.

For line relays the Lackawanna utilized most of the d-c relays in service prior to electrification by inserting individual transformer rectifiers at the relays, thus accommodating a-c line circuits. Where three position relays were advantageous, for instance, for switch indications, a-c relays were employed.

The interlocking plants were either electro-mechanical or electro-pneumatic. Two former mechanical plants were combined in one electro-pneumatic, thus reducing operating expense. Electro-pneumatic switch valve magnets which formerly operated at 14 volts direct current were allowed to remain, a transformer rectifier being inserted in the control circuit of each thus permitting alternating current to be used.

There is no automatic train control effective in the electrified territory of the Lackawanna. However this railroad is operating trains on two-thirds of its main line between Hoboken and Buffalo under a continuous automatic train control system similar to that on the Reading. Trains operate under this protection for 3,600,000 miles per annum.

The signal and interlocking system on the Reading Railroad as described represents the highest grade construction and is in strict accordance with American Railway Association standards. It is evident to anyone who has inspected this that the materials used and construction methods followed are such as will insure long life and low maintenance expense as well as provide for the safe and expeditious handling of trains through the busy Philadelphia suburban district.

**G. H. Dryden:** The Baltimore and Ohio Railroad Company placed in service July 16, 1905 at Bellaire, Ohio, a system of switches and signals wherein one leverman-operator controls train movements over the Ohio River Bridge.

Three ends of double-track and one single-track junction are included in the installation. At the east end of the bridge viaduct a single track connects with the double-track line leading to Grafton, West Virginia and at the west end of the bridge viaduct the single-track line branches into a double-track line toward Newark, Ohio. Near the west shore of the Ohio River there is a branch line junction leading toward Cleveland. The total distance between the extreme ends of double track is 4,841 feet, and the farthest switches and signals from tower are 3,610 feet. Switches and signals are operated by 110-volt d-c motors, and information relating to the location of trains, the position of signals, etc., is obtained through the use of semaphore type tower indicators. No. 4 gauge wire was used in the control of the switch located at the east end of the viaduct. Trains are operated by signal indication. The combined system represents a simple form of centralized traffic control, and apparently the only reason for not having extended this system to include track sections of greater length, was due to the quantity of copper wire necessary.

The Berwick-Stanley installation on the New York Central Railroad is known as the unit wire control system, under which signals are transmitted over one wire for the control of: one switch in both normal and reverse positions; signals protecting the switch in each direction, and also for supplying information to the tower as to the passage of trains over the switch.

This system requires but one wire and common return from the central tower to each switch and is particularly adaptable at gauntlets and other points where the distances are not too great.

Under the code system it is possible to control any desired number of functions throughout a dispatcher's district, using two, three or a maximum of four line wires with the same degree of accuracy as is accomplished where an independent circuit is installed for the performance of but one duty.

Dual control switch machines mentioned in the paper are a recent achievement of manufacturers, without which numerous train delays would occur.

Controlled switches at ends of double track and passing sidings are in certain instances several miles from the headquarters of a maintainer, and should a failure occur due to obstruction in points, misadjustment, blown fuse or other cause, the dispatcher is unable to handle the switches by motor; this duty may be performed by trainmen at his direction. Also where train shifting is necessary, the duty of handling switches is assigned trainmen, thus enabling the dispatcher to devote his time to trains that are moving.

In conclusion, I desire to state—the C-T-C Code System of the Union Switch & Signal Company and the General Railway Signal Company, as well as the Unit Wire Control System, all of which are in successful operation on The Baltimore and Ohio Railroad, have passed the experimental stage, and that through their use track capacity is increased; the number of employees required in operation is lessened, and the running time of trains over a division is reduced.

# Low Frequency Self-Exciting Commutator Generator

BY J. I. HULL*
Member, A.I.E.E.

### Background and Fields of Application

WITH the exception of such profuse outpourings of ideas as follow a fundamental scientific discovery or a basic invention, it is seldom that the study of a supposedly new field of activity fails to disclose to the investigator many earlier pioneers than himself. Little absolutely original thought is left for discussion; yet new viewpoints can be presented, new details developed, and the visions of past thinkers can be viewed, reconstructed in the newer light of the present and brought closer to the point of maximum service. Thus let the writer hasten to disclaim any pretense to being the sole or the earliest pioneer in the effort to use the self-exciting alternating current commutator generator as a source of electrical power. To consider a few who have in the past been interested in this property the reader is referred to *Alternating Current Machinery—Induction Alternator* by William Stanley and G. Faccioli—TRANS. A.I.E.E., Vol. XXIV, 1905, pp. 851-877, where the use of a small self-excited commutator generator as an exciter for an induction generator is discussed; to certain patents of Arthur Scherbius and writings of Walter Seiz, both at the time of these activities connected with the Brown Boveri Company; to an article on a self-excited three-phase exciter machine with short-circuited stator winding by A. Leonhard appearing in *Archiv für Elektrotechnick* Vol. 20, No. 2, 1928, and the investigation of Minorsky and others. Aside from the record of published literature, the tendency of various forms of a-c commutating apparatus to self-excite has frequently been noted by the writer in his daily practise. Commonly this is in an objectionable form, sometimes requiring careful study for its sufficient control or suppression. An engineer's business is to direct the forces of nature to the purposes of man, and a true engineer normally enjoys his work, but his happiness is complete when he is able to direct a naturally harmful force into useful channels. So the writer has long been waiting for a state in the electrical art to arrive which would justify the effort to turn this harmful property of self-excitation to some valuable service.

Since the output of a synchronous generator of 25 cycles or less is seriously limited by its speed, low frequency applications will be the most attractive for the commutator generator, the more so, as commutating conditions are easier the lower the frequency. If the frequency could be altered independently of the speed, the fields of application would be broadened. The number of likely specific applications for a very low frequency power source is considerable and appears to be increasing. Typical examples needing an auxiliary constant voltage—constant low frequency supply are such machines as printing presses and super-calenders for paper mills, where it is desired to operate induction (or synchronous) motors for adjusting or "barring" at very low, yet *stable* speeds. Another possibility is presented by the drive of rolling mill table roll motors, which for the service conditions can be best built for low frequency. Certain vibratory devices are best operated by 10- or 15-cycle power. Moreover, new possibilities might be opened up for frequently reversing motors, by the use of suitable progressive or continuous changes of both voltage and frequency, whereby reversals can be attained with less time and energy loss. Still another type of application is the drive of a group of machines requiring to be synchronized at all times even during starting, stopping and rest, the members of which might be each actuated by a synchronous motor, all these motors driven in common from continuously varying voltage and frequency. The frequency passes through $O$ with a stable minimum voltage of appropriate value for best working conditions. This increasing number of varied likely possibilities caused the writer and his associates to undertake to make what is possibly the first commercial use of a self-exciting alternating current commutator generator as the prime source of energy for a power machine.

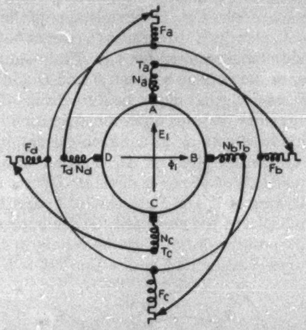

FIG. 1—POLYPHASE SELF-EXCITATION AT $O$ FREQUENCY (DIRECT-CURRENT)

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*General Electric Company, West Lynn, Mass.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

## SELF-EXCITATION IN A COMPLETELY NEUTRALIZED MACHINE

A machine having the armature reaction completely neutralized is suited to give the variety of characteristics and the excellence of commutation needed even for pressures up to several hundred volts. This construction is common for heavy duty direct current apparatus and in alternating current commutating apparatus for the speed and load control of large induction machines. To illustrate the principle, the circle in Fig. 1 represents an ordinary 100 per cent pitch 2-pole direct current type commutator armature provided with four brushes $A$, $B$, $C$ and $D$, spaced 90 deg. Series neutralizing windings $N_a$, $N_b$, $N_c$ and $N_d$ exactly neutralize the magnetizing effect of the rotor current and cancel any transformer voltage developed in the armature by changes of the flux, so that between terminals $T_a$, $T_b$, $T_c$ and $T_d$ there appears only the voltage due to rotation. It is proportional to the rate of rotation, amount of flux and a constant of the machine, and independent of frequency.

Assume the existence of a flux $\Phi_1$ in direction $DB$. Its resulting rotation voltage $E_1$ is in direction $CA$ which is 90 deg in space from $DB$. If the resistance of the circuits of $F_b$ and $F_d$ permits $E_1$ to circulate a current having the magnetizing force required for $\Phi_1$, a steady state exists, since there is no voltage between $B$ and $D$ and no current in $F_a$ and $F_c$ (that might tend to change the flux). Voltage stability depends upon the saturation effect of the magnetic circuit as in a direct current machine. With $\Phi_1$ assumed in direction $AC$, a similar steady condition would exist, $E_1$ being in direction $DB$ and exciting current flowing in $F_c$ and $F_a$ instead of $F_b$ and $F_d$.

If $\Phi_1$ is displaced not necessarily 90 deg but any angle $X$ from the position drawn, then the voltage in direction $CA$ is $E_1 \cos X$ while that in direction $DB$ is $E_1 \sin X$. Field currents will exist in the windings of corresponding axes in similar proportions and give the same resultant total magnetizing force as before but shifted by the angle $X$ from its former direction. Thus the machine can operate equally well and will be stable with flux in any axis. In this poly-axial condition, even with direct current, the system can be regarded as a true polyphase one whose frequency is zero.

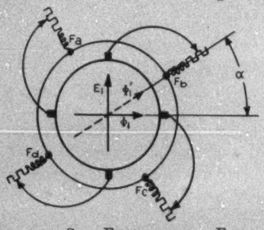

FIG. 2—POLYPHASE SELF-EXCITATION AT FREQUENCY VALUE OTHER THAN $O$ (ALTERNATING-CURRENT)

Fig. 2 represents such a machine with the neutralizing windings (though assumed to exist) omitted from the drawing for simplicity. However, the exciting windings $F_a$, $F_b$, $F_c$ and $F_d$ instead of being arranged to act 90 deg from the rotation voltage axis are now assumed to be rotated $\alpha$ deg in the machine from that position. The rotation voltage $E_1$ due to flux $\Phi_1$ would thus when acting alone, not tend to support the flux $\Phi_1$ but the flux $\Phi_1'$ shifted $\alpha'$ from $\Phi_1$. If the resistance of the exciting circuits be decreased to cos $\alpha$ times its former value, $\Phi_1'$ has a component $\Phi_1' \cos \alpha$ equal to $\Phi_1$ in magnitude and direction, so there can be no collapse of voltage. But the out of phase component $\Phi_1' \sin \alpha$ indicates a field rotating at infinite velocity, as the assumed flux $\Phi_1$ sustains, at the same time not only itself but also a component in advance of itself in space, thus advancing $E_1$ at the same time. Any rotation of the flux, however, will result in the generation of transformer (or reactive) voltages in the exciting windings. With a steady state these cause the exciting current to lag just enough to magnetize at every instant in the (changing) direction of $\Phi_1$ rather than that of $\Phi_1'$. At some particular frequency a stable state with a continuously revolving field can exist, because the component of $E_1$ which remains to balance the $IR$ drop is $E_1$ cos of angle of time lag (which angle must of course be equal to $\alpha$); with our new value of field circuit resistance reduced in ratio of cos $\alpha$ to 1, this component of $E_1$ will just circulate the field current needed to sustain $\Phi_1$. We have drawn Fig. 3 in order to find the relations between the voltage

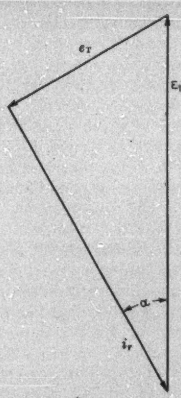

FIG. 3—FIELD CIRCUIT RELATION

$E_1$ = rotation voltage
$e_T$ = transformer voltage in exciting winding
$\alpha$ = axis shift and time lag angle
$\Phi_1$ = working flux
$\sim$ = frequency
$N_1$ = field winding turns
$i$ = field circuit current
$r$ = field circuit resistance

($E_1$), frequency ($\sim$), speed (rpm), number of exciting turns ($N_1$) and axis shift ($\alpha$) of the exciting winding from its zero frequency or direct current position. The following equations may be written:

$$e_T = E_1 \sin\alpha \text{ (for symbols see Fig. 3)} \quad (1)$$

$$E_1 = \Phi_1 \, RPM. \, K \qquad (K = \text{machine constant}) \quad (2)$$

$$e_T = 4.44 \, \Phi_1 \sim N_1 \, 10^{-2} \quad (3)$$

Substituting (**2**) in (**1**) in (**3**)

$$\sim = \frac{K_2 \, RPM \sin\alpha}{N_1} \qquad \left(K_2 = \frac{K \, 10^2}{4.44}\right) \quad (4)$$

We notice the interesting fact that the frequency is dependent only upon rpm, angle of axis shift, number of turns in exciting winding, and a constant $K_2$. ($K_2$ depends upon the number and disposition of rotor conductors.)

We may also write for the field circuit resistance drop

$$ir = E_1 \cos\alpha \quad (5)$$

which is of the same form as for the shunt field circuit of a direct-current machine. So we conclude that, as in a direct-current generator, we can adjust the voltage by changing resistance in series with the shunt-field winding, without in any way affecting the frequency. The stability of the voltage, at a given setting, as with a direct-current generator is dependent upon saturation. The condition of self-excitation with a direct-current generator is that the resistance drop of the exciting current of a given flux be not more than the rotation voltage of that flux. With the alternating-current machine the condition is that the resistance drop be not greater than the rotation voltage times the cosine of the angle of axis shift, or,

$$ir \leqq E_1 \cos\alpha \quad (6)$$

Were it possible suddenly to alter $\alpha$, the frequency corresponding to the new position (if (**6**) is satisfied for any voltage) should be assumed at once, but if the new condition requires a different magnitude of voltage, the change of magnitude should be gradual as is the case with a direct current generator. So, to initiate self-excitation, the priming flux has theoretically any finite magnitude and frequency; upon release from the priming flux energy source, the machine promptly assumes its normal frequency and gradually assumes its normal voltage. These anticipated characteristics were verified by tests, during which residual flux often proved a sufficient prime to initiate self-excitation.

## PLAIN SHUNT EXCITATION

Since the foregoing formulas are exact only if the rotation voltage ($E_1$) and terminal voltage ($E_T$) are identical, it is of interest to consider the performance, not only running light but also when a load current is taken off, as this will introduce a difference between the generated and the terminal voltage. In Fig. 4 we have shown relations in a plain shunt excited machine. The running light condition is similar to Fig. 3, generated voltage $E_0$ being $OD$, reactive field drop or transformer voltage of the flux being $DE$ and field circuit resistance drop being $EO$. $CB$ and $BA$ are resistance drop and reactance drop of load current $I_1$, and the resultant terminal voltage $OA$ will evidently be less than $OD$. If the working flux is by this fact reduced, $OC$, the generated voltage will be less than $OD$. The angle $\alpha$ remains constant at all steady states of excitation, as does the angle between $AG$ (or $DE$ or $CF$) and $OCD$. (Note that $\alpha$ is the "axis shift angle" no longer equal to the power factor angle of the field impedance drop.) We can see, then, first that stability obtains when the relations between $OD$, $OE$, $OC$ and $OG$ are as shown in saturation curve 4$A$ for the corresponding quantities $od$, $oe$, $oc$ and $og$ and in which $oe$ = magnetizing current for no-load generated voltage $od$, and $og$ = magnetizing

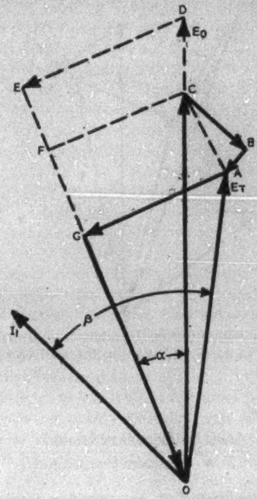

FIG. 4—SHUNT SELF-EXCITATION UNLOADED AND LOADED

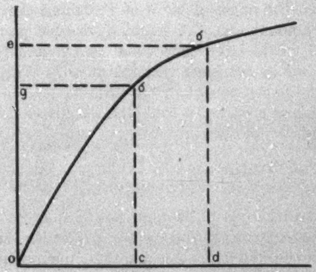

FIG. 4A—SATURATION CURVE

current for full load generated voltage *oc* (the field current resistance drops *OE* and *OG* are proportional to field currents *oe* and *og*). We can see secondly that the ratio of *AG* to *OC* is a measure of the frequency, since with constant speed *OC* is proportional to the working flux while *AG* is proportional both to this flux and to its frequency (being an induced voltage. Since $\frac{CF}{OC} = \frac{DE}{OD}$ it follows that

$$\frac{AG}{CF} = \frac{\text{frequency loaded}}{\text{frequency unloaded}}.$$

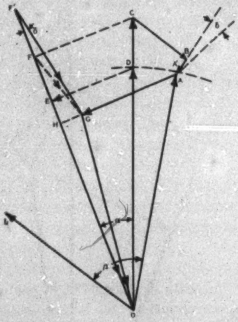

Fig. 5—Self-Excitation Loaded and Unloaded Flat Compounded as to Both Voltage (*OA*/*OD*) and Frequency (*AG*/*CF*)

As drawn, the frequency has somewhat increased and the voltage has decreased as the load current $I_1$ came on. Had the angle of lag $\beta$ of $I_1$ behind *OA* been a certain amount less, *CA* would have been parallel to *FG*, *AG* would have been equal to *CF* and the frequency would not have changed at all. With a still less reactive component in the load current, or a pure watt load or a capacity load, the frequency decreases with load.

## Compound Excitation for Constant Voltage and Frequency

These variations of voltage and frequency can be magnified or reduced, and for any particular load condition can be eliminated entirely by compounding.

In Fig. 5 we illustrate a condition of flat compounding wherein a series excitation has been added so as to maintain the same terminal voltage and the same frequency with the load current $I_1$ as at no load. Thus *OA*, terminal voltage with machine loaded is numerically equal to *OD*, no-load generated and terminal voltage, and is the resultant of *OC* the generated voltage with machine loaded, and the reactance and resistance drops *BA* and *CB* of the load current $I_1$. The "reactance drop" *BA* is defined as the true reactance drop *BA'* plus the voltage *A'A* generated in the series exciting winding by transformer action of the main flux. In the shunt exciting circuit, the induced voltage *AG* at a constant angle (90° + $\alpha$) from *OC* must equal *CF* in order, with flux corresponding to *OC*, to have the same frequency as at no load (measured by $DE/OD = CF/OC$). Thus the resistance drop *GO* (and so the shunt field current) is neither of correct phase nor magnitude to excite the required flux for *OC*. If there were no saturation effect such a fictitious resistance drop would be *FO*, but as the iron density has risen, the shunt field current would have to be increased more than directly as *OC*/*OD* so that the actual resistance drop of the shunt field current that would be needed is represented by *F'O*. So, actually to have the requisite compounding we must supply in addition to the shunt exciting winding a series winding such that from $I_1$ will be derived the same ampere turns as would come from the shunt winding if it carried the current corresponding to drop *F'G*. The voltage induced by the working flux in such a series winding would be a plain reactance drop lagging 90 deg if there were no other ampere turns in the circuit, but since the actual total ampere turns are proportional to *F'O* which is $\delta$° out of phase with *F'G*, the "reactance drop" of the series winding is shown as *A'A*, shifted $\delta$° from *BA'*, the true leakage reactance drop.

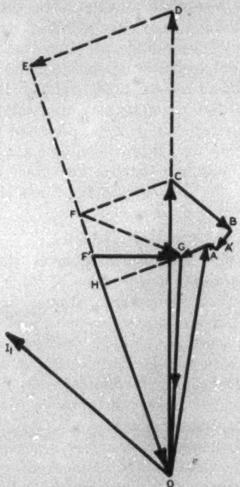

Fig. 6—Self-Excitation Loaded and Unloaded Compounded for Falling Voltage (*OA*/*OD*) and Falling Frequency (*AG*/*CF*)

The series excitation required for flat compounding of both voltage and frequency serves the purpose of supplying that excitation needed to generate a voltage to overcome the resistance and "reactance" drop of the main circuit, and save for the variations of saturation effect would (neglecting $AA^1$) be correct for constant terminal voltage and frequency with all values of load current $I_1$ as well as for the particular one illustrated.

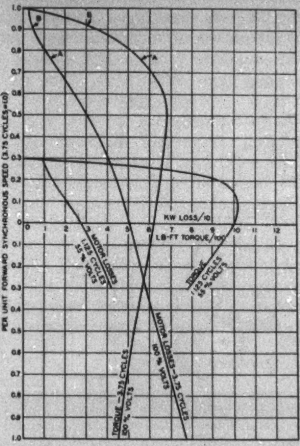

Fig. 7—Motor Performance with Two Sets of Voltage and Frequency Conditions

## Compound Excitation for Falling Voltage and Frequency

Fig. 6 is drawn to illustrate voltage and frequency simultaneously decreased with load $I_1$, by suitable compounding. The no-load generated and terminal voltage is $OD$, full load generated voltage $OC$, and terminal voltage $OA$. No-load frequency is measured by $DE/OD = CF/OC$ and full load frequency is measured by $AG/OC$, hence as load changes from $O$ to $I_1$, voltage changes from $OD$ to $OA$ and frequency from $CF$ to $AG$. We can choose the compounding effect so that percentage change in frequency is more or less than the change in voltage as we wish.

In this case the generated voltage $OC$ being less than the no-load value $OD$, there is required an equivalent shunt field resistance drop $F'O < FO$ because of decreasing saturation, hence the needed series winding effect will correspond to resistance drop $F'G$ and not $FG$.

As is the case when voltage of a direct current generator is varied by field resistance manipulation or by series windings, there is a certain favorable voltage range as governed by the saturation curve of the machine in which the voltage and frequency can be stably manipulated as described above, but outside such range instability occurs. There are various ways beyond the scope of this article whereby the stable range may be so extended as to include very small voltage values even at zero frequency when desired, either with compound excitation or with adjusted shunt excitation, or both.

## Reversal of Induction Motor by Voltage and Frequency Control

Fig. 7 has been calculated in order to show the advantage that could be obtained in a frequently reversing induction motor even at low running frequency, if it were reversed in several steps of both voltage and frequency rather than by "plugging." Speed-torque and speed-loss curves supply data for calculations (not reproduced here) to illustrate this point. It is found that with a fixed value of 100 per cent volts and 3.75 cycles, a certain motor whose inertia is $WR^2$ can be "plugged" from + 90 per cent to − 80 per cent rpm in 1.7 second with an internal loss of 76.7 kw-seconds and the effective torque value is 560 lb-ft. If the reversal is obtained by passing in steps from 100 per cent volts, 3.75 cycles to 55 per cent volts 1.125 cycles, then to 55 per cent volts 1.125 cycles reversed phase sequence and finally to 100 per cent volts 3.75 cycles, reversed phase sequence, the reversal can still be done in 1.7 second but with an internal loss of 36 kw-seconds, or 47 per cent as much internal heating as in plugging.

A similar study indicates that reversal by passing from forward rotation to direct current then to backward rotation, would produce 64 per cent as much heating as straight plugging.

Still better reversal can be obtained if voltage and frequency are smoothly changed from one rotation to the other so as to have the motor always operate at a portion of its curve which yields large torque in proportion to losses. This process will best be apprehended by realizing that the torque and the $I^2R$ losses (which will be the largest portion of the losses) are constant for given values of primary current and rpm slip, irrespective of the actual speed, frequency and voltage.

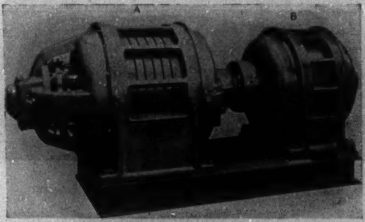

Fig. 8—G.E. 40-Kva 2.5-Cycle Frequency Converter Set

(A) 40-kva, 235-volt, 2.5-cycle self-excited generator
(B) Squirrel-cage induction driving motor

So if we suitably vary voltage and frequency we can carry out the reversal at a constant value of torque and loss selected from the motor curves, such as $AA$, Fig. 7, wherein the torque is 560 and the losses 13 kw. The time still being 1.7 seconds, we find the heating to be

1.7 × 13 = 22.1 kw-seconds or 29 per cent of that due to straight plugging.

At points *BB*, torque 300, time is 3.17 seconds, losses 4.5 kw, kw-seconds 14.25 or 18.7 per cent of the heating due to plugging.

Neglecting saturation, the time of a reversal can be adjusted by using more or less voltage without affecting the stored heat losses, since both torque and losses vary approximately as the square of the voltage. So, when not operating within zones of high saturation it may be advantageous to operate much below the maximum torque point, or at *BB*, securing the desired speed of reversal by the use of a higher voltage.

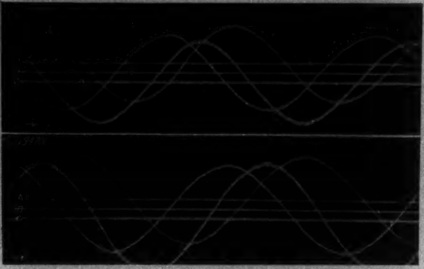

FIG. 9—OPEN CIRCUIT VOLTAGE WAVE FORM FOR 200 VOLTS (ABOVE) AND 285 VOLTS (BELOW)

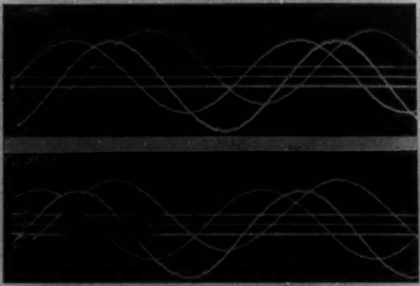

FIG. 10—VOLTAGE WAVE FORM WHILE LOADED

(Above) Terminal volts 235, load current 165 amperes at low power factor
(Below) Terminal volts 225, load current 125 amperes at low power factor 75 per cent
Rated current is 100 amperes

## PERFORMANCE RECORDS OF A COMMERCIAL MACHINE

An actual self-exciting generator of the type described has been constructed and tested. It is a 6-pole, 1,200-rpm three-phase machine rated 40 kva, 235 volts, 2.5 cycles, and driven by a squirrel-cage induction motor. The set is shown in Fig. 8, *A* being the self-excited generator, *B* the driving motor. The function of this set is to supply 2.5-cycle 235-volt power to one or more 200-hp super-calender induction motors in order to secure threading operation at very low stable speed. The generator was compounded for approximately flat voltage and frequency as described in connection with Fig. 5, and but very slight changes with load of either voltage or frequency were present after the correct operating brush position was obtained. Commutation was excellent. The voltage wave form was very acceptable as shown in Figs. 9 and 10, although no special study of this detail was made.

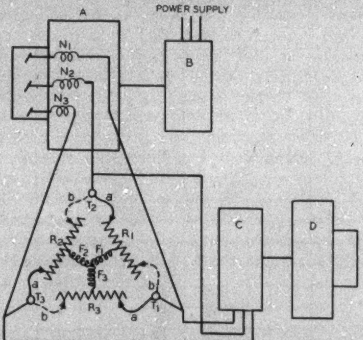

FIG. 11—SHUNT SELF-EXCITATION CONNECTIONS FOR REVERSING PHASE SEQUENCE AND *O* PHASE SEQUENCE WITH LOADING SET *C-D*

Fig. 11 shows the simple arrangement used for obtaining various voltages and frequencies of both phase sequences as well as zero phase sequences (direct current). *A* is the low frequency generator, *B* its driving motor, *C* is a 200-hp 480-rpm induction motor used as a power and reactive load for *A*. It is coupled to a heavier direct current generator *D* both for greater inertia and to be able to control the energy load. The connections are drawn for shunt excitation, three-phase, compounding windings not shown. $N_1$, $N_2$, $N_3$ are neutralizing windings, $F_1$, $F_2$, $F_3$ the shunt exciting windings equipped with double ended rheostat $R_1R_2R_3$. When $F_1F_2F_3$ are connected through connections *aaa*

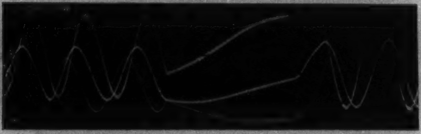

FIG. 12—OPEN-CIRCUIT TRANSITION FROM FORWARD PHASE SEQUENCE TO APPROXIMATELY ZERO TO REVERSED PHASE SEQUENCE

the angle of axis shaft ($\alpha$) of the exciting winding is + 60°, and thus any balanced connection to the "$a$" ends of $R_1R_2R_3$ gives 2.5 cycles positive rotation; voltage depending upon amount of resistance. Connecting through $bbb$ to the "$b$" ends of $R_1R_2R_3$, as shown, changes the axis shift ($\alpha$) by 120 deg resulting in an axis shift of − 60 deg, a frequency of − 2.5 cycles (reversed phase sequence. If both the $a$ and $b$ connections are closed together with $a$ and $b$ resistances equal, the result is axis shift ($\alpha$) equal to zero, and frequency equal to 0. If $a$ and $b$ resistances are unequal, the direction of phase sequence is determined by the lower. By setting the $a$ and $b$ resistances equal, with a three-pole switch (or contactor) in each branch we can change quickly from 2.5 cycles condition ($a$ switch closed) to 0 cycles ($a$ and $b$ switches closed) to 2.5 cycles negative ($b$ switch only closed).

In carrying out this manipulation as recorded in Figs. 12 and 13, a perfect balance was not obtained between the $a$ and $b$ ends of the rheostat so that the intermediate stage (both switches closed) gave a very low frequency rather than exactly zero frequency or direct current.

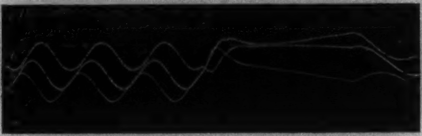

FIG. 13—LOADED TRANSITION FROM FORWARD PHASE SEQUENCE TO APPROXIMATELY ZERO TO REVERSED PHASE SEQUENCE

When the record shown in Fig. 12 was made, the machine was operated on normal phase sequence ($a$ switches closed) and 200 volts 2.5 cycles up to a certain point at which the $b$ switch was also closed giving nearly 0 axis shift and phase sequence, until switch $a$ was suddenly opened again changing the angle of field axis shift from approximately 0 deg to − 60 deg and giving, as may be seen, reversed phase sequence. In Fig. 13 the same manipulation was carried out but the 200-hp 40-cycle induction motor $C$ of Fig. 11 direct coupled to the much heavier direct-current generator $D$ was connected to the low frequency generator terminals throughout the test. The load set $CD$ appeared to the eye to run smoothly up to the point of closing switch $b$, where it seemed to drop instantly to a speed nearly equal to 0, and then instantly to come up to speed in reverse direction when switch $a$ was opened. Figs. 12 and 13 clearly show the prompt response of the frequency to a change in the field circuits.

Fig. 14 shows build-up of self-excitation by a rather large direct current impulse in the field circuit with field rheostat set for 200 volts, and Fig. 15 shows build-up with a very small direct current impulse and field rheostat adjusted for 280 volts. These are interesting as showing that the frequency assumes approximately its steady state value even during build-up. In Fig. 14 the duration of the impulse terminates where regular voltage waves commence, but in Fig. 15 the impulse is so weak that it is difficult to see just where it ceases. Very careful measurements of frequency with various rheostat settings and voltage also showed it to be independent of rheostat position and voltage. The expectation that self-excitation could be readily started by a small impulse in the field circuit of commercial frequency current either single phase or polyphase was also confirmed by test but no oscillograms taken.

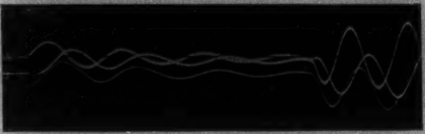

FIG. 14—ESTABLISHMENT OF SELF-EXCITATION BY A STRONG DIRECT-CURRENT IMPULSE IN FIELD CIRCUIT

## CONCLUSION

The above investigation indicates that a practical, flexible, and easily manipulated source of alternating current at frequencies below those advantageous for synchronous alternators is available for moderate cost. It can be controlled so as to serve the many needs known and likely to appear for energy in this form, and unlike various other types of frequency converters can readily be produced with good commutation up to several hundred volts pressure.

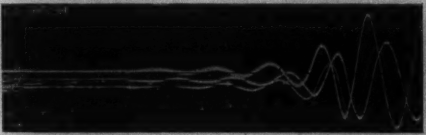

FIG. 15—ESTABLISHMENT OF SELF-EXCITATION BY A WEAK DIRECT-CURRENT IMPULSE IN FIELD CIRCUIT

## ACKNOWLEDGMENT

The author is pleased to state that Mr. P. W. Robinson ably contributed a valuable part of the work of designing and testing the low frequency generator herein described.

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# Discussion

**F. M. Roberts:** From the application standpoint Mr. Hull's important contribution to the electrical art is the provision of a low frequency power supply that can be driven directly from the plant power bus, regardless of the voltage or frequency of the latter. Previous machines used for the purpose of furnishing a low frequency supply have been of the frequency changer type, with commutator, and usually have required a transformer for system voltages over 550. Thus the application engineer has been faced with the necessity of providing transformers to obtain the required low voltage. This, of course, increased the price of the equipment, decreased the efficiency and increased the complexity of the installation.

The design of the Hull low frequency generator permits considerable choice of voltage. This is an important consideration because the inherent characteristics of slip-ring induction motors necessitate that, if normal torque characteristics are to be maintained in starting, a voltage be available at low frequency greater than the voltage calculated in direct proportion to the line frequency. As an example of this point, the generator designed for operating super-calenders during threading at the plant of one of the largest paper mills in Maine supplies power to slip-ring motors whose rating is obtained at 2,200 volts, 40 cycles. The low frequency generator is rated two and one-half cycles, 235 volts, thus the increase of slip ring motor resistance in per cent of the total impedance, which occurs at low frequency is offset by the increased applied voltage, and the induction motor torque output is not limited as it otherwise would be. The previously used frequency changer type of low frequency source has not been suitable for voltages high enough for induction motors wound for use on 2,200-volt systems.

The generator, in addition to providing considerable choice in the selection of the low voltage also exhibits good voltage regulation characteristics so that the operation of a battery of machines, such as super-calenders, which require a high breakaway torque is quite practical as the starting of one unit does not materially interfere with the threading operations on the others.

The control equipment required by this type of generator is no more complicated than that which is furnished for a compound wound d-c exciter. No involved and special control features are required.

The generator is driven by a squirrel cage induction motor, or by a synchronous motor, which may be designed for operation from a power supply of any standard voltage and frequency.

**P. W. Robinson:** Some of the characteristics that attracted special attention during the design and testing of the 40-kva machine mentioned in the paper were the adaptability for compounding the voltage even with a low power factor load and the apparently instantaneous reversal of phase sequence resulting from the appropriate change in shunt field connections. It was quite impressive to see the no-load voltage of an a-c generator maintained or even increased when a substantial overload at low power factor was suddenly applied by closing a line contactor and likewise to see the immediate reversal of the large induction motor, taking its power from the low frequency generator, accomplished by the mere reversal of the generator field switch. The effect of the phase sequence reversal on the compounding also was quite noticeable. Part of the compounding was accomplished by under compensation and this component is reversed in its effect when the phase sequence is reversed. This characteristic can readily be used to cushion the shock to the generator and to the apparatus driven from such a generator, which would otherwise be encountered in plugging by phase sequence reversal of the generator.

It was gratifying to find that tests confirmed the expectation that field flashing can easily be accomplished from either a d-c or an a-c source as the residual flux is reduced to a very small amount if the machine comes to rest with the field switch closed.

There probably is a natural tendency to feel that not much starting torque will be obtained from an induction motor if the flux rotates slowly around the stator, as is the case with a low frequency power supply. Calculation shows, however, that excellent starting torque will be obtained if the voltage applied is suitable for the changed relations of resistance and reactance as compared with those at normal frequency. Tested starting torque at the low frequency was practically the same as calculated.

# Some Factors Affecting Temperature Rise in Armatures of Electrical Machines

BY CARL J. FECHHEIMER*

Fellow, A.I.E.E.

THE treatment given herewith is applicable to the steady state, that is, the machine has been run for such length of time that the temperatures have ceased to rise. It can readily be extended so as to apply to the transient state as well. The author received valuable suggestions from Mr. A. Tustin, Metropolitan-Vickers Electrical Co., Ltd., during a business association some years ago.

Assume that the machine is run without load, but at normal speed and with such excitation that there is normal voltage generated. Then, after the steady state is reached, the losses in the iron cause a certain temperature rise of the iron, and by conduction of heat through the insulation there is also a temperature rise of the copper, but less than for the iron. While, in the usual case, most of the heat generated in the iron is conducted along, or across, the laminations to the surfaces from which the heat is dissipated, a smaller amount escapes into the copper, is conducted axially along the copper, and then, through the insulating wall at the vent ducts, or on the ends, to the air. If $P_2$ is the iron loss, $\theta_1$, the copper, and $\theta_2$ the iron temperature rise,

$$P_2 = K_{22}\theta_2 + K_{21}(\theta_2 - \theta_1) \qquad (1)$$

Here, $K_{22}$ and $K_{21}$ are respectively the net heat transfer factors, or conductances, from the iron to the air, and from the iron to the copper. Equation (1) means that of the total heat per unit of time generated by iron loss, the part $K_{22}\theta_2$ escapes direct to the air, and the part $K_{21}(\theta_2 - \theta_1)$ is conducted through the insulation to the copper, and, after flowing longitudinally along the copper, escapes through the insulating wall to the air at the vents or at the ends.

Similarly, if the machine is run on short circuit, with full-load current, and the iron losses are negligible,

$$P_1 = K_{11}\theta_1 + K_{12}(\theta_1 - \theta_2) \qquad (2)$$

($P_1$ is the copper loss, $K_{11}$ and $K_{12}$ respectively the net heat transfer conductances from the copper to the air and from the copper to the iron.) That is, some heat, $K_{11}\theta_1$ escapes at the vent ducts and ends directly to the air, and the remainder, $K_{12}(\theta_1 - \theta_2)$, is conducted through the insulating wall to the iron, whence it flows through the iron package to the surfaces at the vent ducts, to be picked up by the moving air streams.

The equivalent thermal circuits may be shown as for a model in Fig. 1. Here $\theta_a$ is the air temperature, and since only rises of temperature above $\theta_a$ are being considered, $\theta_a$ is zero for reference. The heat transfer factors $K_{11}, K_{12}\ (= K_{21})$ and $K_{22}$, are shown as conductances for heat flow.

A better understanding may be obtained from the equivalent electrical circuit, shown schematically in Fig. 2. The temperatures, being thermal potentials, are equivalent to emfs, $e_1$ and $e_2$ and the conductances $K_{11}$, $K_{12}$, and $K_{22}$ are the equivalents of the reciprocals of resistances. The currents are the equivalents of the rate of heat flow, or of the losses. Evidently,

$$i_2 = K_{22}e_2 + K_{21}(e_2 - e_1)$$
$$i_1 = K_{11}e_1 + K_{12}(e_1 - e_2)$$

These are the exact equivalents of equations (1) and (2). From the electrical analogy, it will be evident that the conditions that obtain when there are copper and iron losses simultaneously are the same as secured by superimposing the copper loss upon the iron loss with each source of heat acting alone. Therefore, equations (1) and (2) hold also when the two sources of heat act simultaneously.

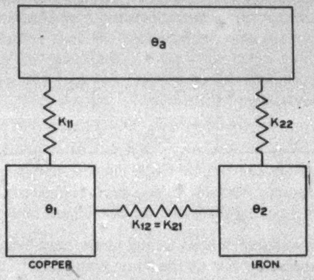

FIG. 1

Solving equations (1) and (2), for the temperature rises, we obtain:

$$\theta_1 = \frac{(K_{21} + K_{22})P_1 + K_{12}P_2}{K_{11}K_{22} + K_{12}K_{22} + K_{11}K_{21}} \qquad (3)$$

$$\theta_2 = \frac{K_{21}P_1 + (K_{11} + K_{12})P_2}{K_{11}K_{22} + K_{12}K_{22} + K_{11}K_{21}} \qquad (4)$$

Or,

$$\theta_1 = R_{11}P_1 + R_{12}P_2 \qquad (5)$$

$$\theta_2 = R_{21}P_1 + R_{22}P_2 \qquad (6)$$

Where

$$R_{11} = \frac{K_{21} + K_{22}}{K_{11}K_{22} + K_{12}K_{22} + K_{11}K_{21}} \qquad (7)$$

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

$$R_{12} = R_{21} = \frac{K_{12}}{K_{11}K_{22} + K_{12}K_{22} + K_{11}K_{21}} \qquad (8)$$

$$R_{22} = \frac{K_{11} + K_{12}}{K_{11}K_{22} + K_{12}K_{22} + K_{11}K_{21}} \qquad (9)$$

Similarly, if $R_{12} = R_{21}$, the conductances equivalent to the resistances may be obtained:

$$K_{11} = \frac{R_{22} - R_{12}}{R_{11}R_{22} - R_{12}^2} \qquad (10)$$

$$K_{12} = K_{21} = \frac{R_{12}}{R_{11}R_{22} - R_{12}^2} \qquad (11)$$

$$K_{22} = \frac{R_{11} - R_{12}}{R_{11}R_{22} - R_{12}^2} \qquad (12)$$

Equations (5) and (6) could be obtained directly from the principle of superposition in the theory of potential. As applied to the thermal circuit, it may be stated as follows: The temperature rise at any point of a system due to one source of heat, acting alone, may be added to the temperature rise at the same point due to another source of heat also acting alone, and the sum will equal the temperature rise at that point if both sources supply simultaneously the same amounts of heat as before.

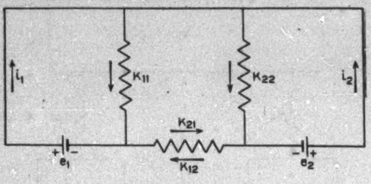

FIG. 2

That $R_{12} = R_{21}$ follows from the principle of reciprocity, which for the heat circuit is that the temperature rise of part 1 due to one watt loss in part 2 equals the temperature rise of part 2 due to one watt loss in part 1. In other words, if two bodies are separated by a heat conducting medium, the temperature difference is numerically the same for a given quantity of heat flow, regardless of the direction of flow, although there is a reversal of sign.

The determination of the coefficients, $R_{11}$ $R_{12}$ and $R_{22}$ by calculation is somewhat involved.* However, they can readily be obtained from tests. Thus, if the machine is run on open circuit until the steady state is reached,

$$P_1 = 0, \text{ and } R_{12} = \frac{\theta_1}{P_2} \text{ and } R_{22} = \frac{\theta_2}{P_2}.$$

If the machine is subsequently short-circuited, and the temperature is again measured in the places as before,

$$P_2 = 0, \text{ and } R_{11} = \frac{\theta_1}{P_1} \text{ and } R_{21} = \frac{\theta_2}{P_1}.$$

The losses may be taken, say, for one tooth pitch per unit length axially and it then will be convenient to compare the coefficients for different machines of approximately the same slotting. Or better, if comparisons are to be made for machines for which the slotting differs considerably, the losses should be per unit of periphery and per unit length axially, that is per unit area of armature surface. Nearly all designers now calculate the ampere conductors per inch of periphery, which is one of the determining factors in the copper loss per unit cylindrical surface. In general, the iron loss should be taken only as the tooth loss, as in many cases, the heat generated in and dissipated from the core has nearly negligible influence upon the tooth temperature, as the loss in the core is transferred to the air streams in the core vents; and similarly for the losses in the teeth. The eddy current loss in the embedded conductors should in all cases be added to the $I^2R$ loss therein.

The copper temperature rise $\theta_1$ should preferably be taken by an embedded detector. It is also desirable to measure the iron temperatures by a detector embedded in the teeth, but if this can not readily be done, the tooth surface temperature may be measured in the usual way. It is important that all measurements be made in the same spots for the several temperature tests. Even when copper temperature measurements by detector can not be made, temperatures by thermometer, or by resistance can be taken. With higher temperature rises, suitable corrections should be made for the increase of copper loss with temperature. When the air temperature rise is appreciable, it is also advisable to allow for the departure in air temperature adjacent to the part considered at load from that which obtained in the tests on open and short circuit. Then equations (5) and (6) should be written,

$$\theta_1 = R_{11}P_1 + R_{12}P_2 + \theta_a \qquad (13)$$

$$\theta_2 = R_{21}P_1 + R_{22}P_2 + \theta_a \qquad (14)$$

Now $\theta_a$ is the air temperature rise above the ingoing air up to the part considered for the particular test. Thus, when run on open circuit, and $P_1 = 0$,

$$R_{12} = \frac{\theta_1 - \theta_{a2}}{P_2} \qquad (15)$$

$$R_{22} = \frac{\theta_2 - \theta_{a2}}{P_2} \qquad (16)$$

In both equations $\theta_{a2}$ appears because it is assumed that the air temperature rise is the same whether the

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*A means for determining these coefficients analytically is given in a paper by C. R. Soderberg on the *Steady Flow of Heat in Large Turbine Generators*, A.I.E.E. TRANS., 1931, Vol. 50, No. 2, p. 782.

copper or iron temperature rise is considered. The subscript 2 signifies that the test is made with iron loss only.

When run on short circuit, $P_2 = 0$, and

$$R_{11} = \frac{\theta_1 - \theta_{a1}}{P_1} \tag{17}$$

$$R_{21} = \frac{\theta_2 - \theta_{a1}}{P_2} \tag{18}$$

When calculating the load temperature rises from equations (**13**) and (**14**), the air temperature rise $\theta_a$ for the load condition must be used instead of $\theta_{a1}$ or $\theta_{a2}$.

To correct for the influence of the departure in copper temperature upon the copper loss, and therefore upon the temperature rise, with load, the following method may be used.

Let

$P_1$ = copper loss at the particular location, including allowance for increase in resistance, due to higher copper temperature than obtained on short circuit

$P_1'$ = copper loss at same location as for short circuit test reduced to the same current as for $P_1$, but corresponding to $\theta_1'$

$\theta_1$ = copper temperature rise for load conditions, as for $P_1$

$\theta_1'$ = copper temperature rise for short circuit conditions

$\theta_a$ = air temperature rise for load conditions

$\alpha$ = temperature coefficient of resistance of copper at temperature rise $\theta_1 = \dfrac{1}{234.5 + \theta_1' + \theta_o}$

$\theta_o$ = ingoing air temperature

Other symbols are as before

Then,

$$P_1 = P_1' \,[1 + \alpha\,(\theta_1 - \theta_1')] \tag{19}$$

Substituting the value $P_1$ from equation (**19**) in equation (**13**) and solving for $\theta_1$,

$$\theta_1 = \frac{R_{11}P_1'\,(1 - \alpha\theta_1') - R_{12}P_2 + \theta_a}{1 - R_{11}P_1'\alpha} \tag{20}$$

also,

$$\theta_2 = R_{12}P_1 + R_{22}P_2 + \theta_a \tag{21}$$

$$= R_{12}P_1' \,[1 + \alpha\,(\theta_1 - \theta_1')] + R_{22}P_2 + \theta_a \tag{22}$$

The above assumes that the ingoing air temperature is the same for all cases.

In order to estimate the temperature rise of the air, $\theta_a$, up to the part considered, the temperature rise of the air through the whole machine may be conveniently measured. If the machine is provided with a stationary armature, and the measurements are referred to the middle of the tooth or slot, the losses in the core and in half the slot and tooth depth may be calculated and deducted from the total losses. Then,

$$\theta_a = \theta_{at} \frac{P - P_c}{P} \tag{23}$$

$\theta_a$ is the temperature rise of the air up to the middle of the tooth

$\theta_{at}$ is the total temperature rise of the air

$P$ is the total loss

$P_c$ is the loss in the core + 1/2 tooth + 1/2 embedded copper loss

Or, in designing a machine, the volume of air per unit of time, (cu ft/min), $Q$, and the total watts loss, $P'$, up to the given point, may be estimated. Then,

$$\theta_a = 1.765 \frac{P'}{Q} \tag{24}$$

In a certain machine thermocouples were placed on the bare copper and in the armature tooth laminations. Temperatures were also measured by thermometer and by resistance; for the latter, readings of resistance and time were taken, and the resistance was projected back to the time of removing the load. The example is given only to illustrate the application of the method; it is not intended that the temperature rises are typical of any line of machines. From the open- and short-cuit tests the following values of the coefficients were obtained from the embedded detector measurements:

$R_{21} = 5.6 \quad R_{12} = 6.84 \quad R_{11} = 10.12 \quad R_{22} = 9.27.$

Mean of $R_{21}$ and $R_{12} = 6.22$.

The short-circuit test was made at 125 per cent current. The temperature rise of the bare copper was 60 degrees, and the ingoing air was 26 degrees. Then,

$$\alpha = \frac{1}{234.5 + 60 + 26} = 0.0031$$

The tooth loss per square inch of cylindrical surface was 1.91 watts, and at 125 per cent current and at 60 + 26 degrees total temperature, the copper loss per square inch was 5.04 watts.

Substituting in equation (**20**),

$$\theta_1 = \frac{10.12 \times 5.04\,(1 - 0.0031 \times 60) + 6.22 \times 1.91 + 21}{1 - 10.12 \times 5.04 \times 0.0031}$$

$$= 88.4 \text{ deg. rise}$$

And from equation (**22**), $\theta_2 = 72.7$ deg. rise.

Similar calculations were made for 100 per cent load, for embedded detectors, and for average temperature rise (by resistance) and for temperature rise by thermometer. For the thermometer calculations, the coefficients $R_{11}R_{12}$ and $R_{22}$ were not determined, but the open-circuit and short-circuit temperature rises were simply added and no allowance for air temperature increase or copper resistance made. The justification for neglecting departures in air temperature is that the tests on open and short circuit were for the same voltage and current as for the load conditions as obtained in the 125 per cent load test; the sum of the air temperature rises for the two cases is substantially the same as the temperature rise of the air with load, since the sum of the losses for the two tests are nearly the same as for load. There should be a slight correction downward for the 100 per cent load test, and had this been done the agreement would probably have been better. The results are given in Table I.

TABLE I

| | Temperature rises, deg C | | | |
|---|---|---|---|---|
| | 100 per cent load | | 125 per cent load | |
| | Calculated | Test | Calculated | Test |
| Copper by detector on bare copper | 63.3 | 61.5 | 88.4 | 84.2 |
| Iron by detector in tooth | 57.2 | 58.5 | 72.7 | Not taken |
| Mean copper by resistance | 36.8 | 35.0 | 51.0 | 58.5 |
| Thermometer on iron surface | 40.0 | 39.0 | 54.0 | 55.5 |
| Thermometer on coil ends | 39.2 | 38.0 | 52.5 | 49.3 |

It is believed that the agreement between test and calculated temperature rises is as close as can be expected.

Some designing engineers have estimated the temperature rises with load by adding the copper and iron losses, and then have divided that loss by a surface to obtain the watts per square inch. That method is incorrect except for the remote case for which $R_{11} = R_{12}$ and $R_{21} = R_{22}$. Again, in many machines the copper loss has considerably more influence upon the temperature rise than the iron loss, and the temperature rise is frequently considered to be proportional to the product of amperes per square inch and ampere conductors per inch; that is, to the $I^2R$ loss per unit cylindrical surface. When an attempt is made to correlate test data taken on low-frequency machines with low loss per cu in. in the iron, with data on machines of higher frequency with larger loss density, inconsistencies were obtained, since in the latter the influence of iron loss upon temperature rise can not be neglected. The latter method is also applicable only for given thermal specific resistance of insulation, for the same percentage of eddy currents in the copper, for nearly uniform slotting, and for uniform insulation thickness.

Aside from securing design data, the method is useful for the testing of large machines for which it is costly to make full load tests, and for which the necessary equipment for full load loading is lacking in most test departments. Then, instead of making a full load temperature test, two relatively inexpensive tests are made, one at no load at normal voltage, and the other on short circuit at full load current. The sum of the temperature rises from the two tests at any given location, corrected for increased air temperature rise and for increased copper resistance, is then the full load temperature rise. As previously pointed out, in some machines it is unnecessary to correct for the increase in air temperature rise, and the incremental copper loss due to increase in resistance with temperature is also often negligible; it is well to bear in mind that the eddy current loss in the copper decreases with increase in resistance.

Such tests can readily be made on d-c machines or on salient-pole or turbine alternators. To secure the full load current in the copper in an induction motor, it should be driven at 200 per cent slip, and such voltage applied to the stator that full load current flows. The objection to the latter is that currents of double normal frequency flow in the rotor which with deep bars cause a large eddy current loss. The incremental rotor copper losses can readily be estimated, and an allowance made for the increased air temperature rise due thereto. In a few cases, however, the eddy current losses may produce too high rotor loss, and give rise to a large rotor temperature, and then the method should not be used. On the other hand, most induction motors can be given full load tests at the factory, and it is very seldom that the motor need be shipped without a full load test.

In order to obtain the values of the coefficients $R_{12}$, and $R_{22}$, the induction motor can be run idle at normal voltage, and $R_{12}$ and $R_{22}$ obtained with the aid of equations (**15**) and (**16**). It can then be given a full load test, and then with the aid of equation (**13**) and $R_{12}$ previously found, $R_{11}$ can be calculated. These values can then be used in design of future machines.

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## Discussion

**D. S. Snell:** The paper by Mr. Fechheimer is an interesting and useful addition to the literature on heat flow in electrical machinery. Taking it in connection with a paper by Mr. C. R. Soderberg[1] on a similar subject presented in 1931, it can be said that these two papers serve to reduce the complicated heat flow problem to a form readily solvable by the application of Ohm's and Kirchhoff's Laws, and should therefore encourage on the part of electrical designers a more general attempt to calculate the thermal behavior of their machines by other than "rule of thumb" methods.

It is my feeling, however, that in seeking a simple solution to this problem the author of the present paper has reduced the actual thermal circuit of an electrical armature to such a form that the solution can be applied with accuracy to only a limited class of machines, namely, those machines in which the temperature rise of the ventilating air does not constitute an appreciable fraction of the total rises of the copper or iron, and in which the variation of the air temperature along the armature is small.

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[1] *Steady Flow of Heat in Large Turbine-Generators*, A.I.E.E. TRANS., June 1931, p. 782.

In an armature provided with radial ventilating ducts, the separate packages of iron laminations are virtually insulated from each other thermally, by the air ducts, the only connection between them being the insulated armature conductors and the spacing blocks in the ventilating ducts. The armature conductors, on the other hand, are continuous for the length of the armature, and in addition have a very high thermal conductivity in the axial direction. It follows, therefore, that the temperature rise of any individual package of laminations, as measured by embedded detector, would largely be controlled by the temperature of the air in the ducts on either side of the package; whereas the temperature of the conductor at any point, similarly measured, would be governed less by the air temperature at that point, than by an average of the air temperatures in several ducts on either side of it.

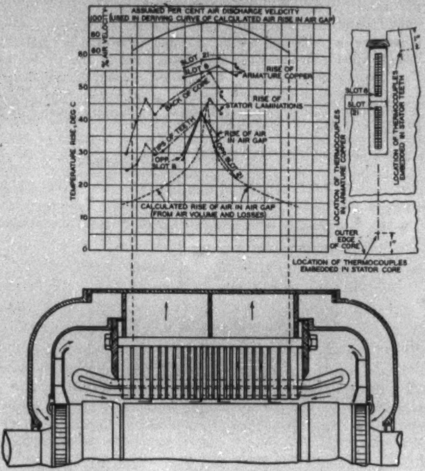

FIG. 1—TEMPERATURE RISES OF STATOR AND VENTILATING AIR FOR A 6,250 KVA 3,600 RPM TURBINE GENERATOR AT 94 PER CENT FULL-LOAD ARMATURE CURRENT, ZERO POWER FACTOR OVEREXCITED

This will be apparent from Fig. 1, which shows the temperature rises of the air, stator copper and stator iron of a 6,250 kva turbine generator, at different points along the armature, as obtained from a test under approximately full load conditions. It will be noted that the curves of temperature rise of the different iron packages follow quite closely the curves of temperature rise of the cooling air, while the temperature of the armature copper is seen to be influenced to a much lesser extent by changes in the air temperature. Fig. 2 shows the results of a similar test on a turbine generator of 43,750 kva. In this machine the cooling air is admitted to the stator from the back of the core as well as from the ends of the air gap, so that the temperature rise of the air is considerably less than for the smaller machine. It is, nevertheless, a considerable fraction of the total rises of the iron and copper, and is shown to influence the temperatures of the separate iron packages in much the same manner as for the smaller machine.

It will be apparent from the above curves that the method of determining the armature temperatures suggested in the present paper, would not apply with accuracy to machines in which the temperature rise of the air along the armature is appreciable, since the method described assumes a single value of the air temperature rise $\theta_a$, which applies to both the copper and the iron. To apply the method with accuracy, would seem to require the assumption of one average air temperature rise to apply to the conductor, and several different air rises to apply to each of several different packages of laminations. A model based on such an assumption is shown in Fig. 3, in which $\theta_{a1}$ is the average air rise over a certain length of the conductor, and $\theta_{a2}$, $\theta_{a3}$, etc., the air rises up to each of the different iron packages. If the iron packages are of equal thicknesses the factors $K_{12}$ and $K_{22}$ will be the same for each package and the circuit can be solved for the different constants by knowing the rises of the copper, air and iron from tests at no-load normal voltage and at full load, short circuit. It should be mentioned that the iron losses under short circuit are not always to be neglected, as the paper implies, since the short-circuit load losses in the stator teeth are sometimes appreciable, especially for turbine generators.

In estimating the average rise of the air in the air gap over a given length of the armature, it is necessary to take account of the variation in air quantity in the gap due to discharge or admission from the radial ducts. If the quantity of air discharged or admitted per duct in a given section of the core is assumed constant, the average air rise in the gap over the section is approximately given by the equation:

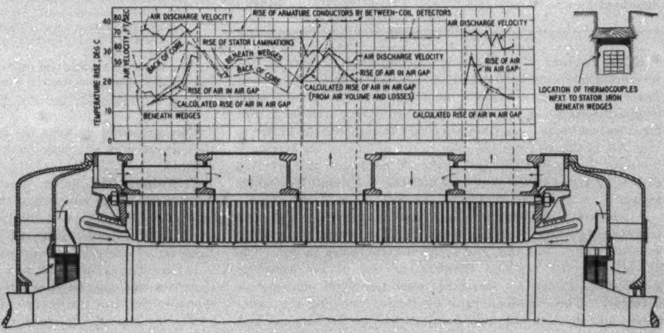

FIG. 2 — TEMPERATURE RISES OF STATOR AND VENTILATING AIR FOR A 43,750 KVA 1,800 RPM TURBINE GENERATOR AT 90 PER CENT FULL-LOAD ARMATURE CURRENT ZERO POWER FACTOR OVEREXCITED

$$\theta_a = \theta_a' + \frac{1{,}765\, LB}{2Q_a} \sum n$$

where

$\theta_a$ = average rise of air in air gap, in section considered, deg C.

$\theta_a'$ = rise of air before entering section of gap, deg C.

$L$ = length of section, in.

$B$ = kw loss to air gap, per in. length of rotor, (consisting of rotational, field $I^2R$ pole face losses and losses from stator teeth tips)

$n$ = number of ducts in the section

$Q$ = total cu ft per min of air to section at 25 deg C

$$\sum n = \frac{2n-1}{n} + \frac{2n-3}{n-1} + \frac{2n-5}{n-2} \ldots \text{(to } n \text{ terms)}$$

From a practical standpoint however, the writer would question whether the proposed method of predicting full load armature temperatures is, even under favorable conditions, appreciably more accurate than the present method of adding together the rises obtained from the tests at no load, normal voltage and full load short circuit and deducting the rise obtained from a test at zero excitation. This method has been used for many years in estimating the full load armature temperatures of turbine generators, and with very satisfactory results. The accompanying table illustrates the application of this method, for a 35,300-kva turbine generator, and the agreement between the estimated and actual temperature rises may be considered entirely satisfactory. In view, therefore, of the good results obtainable from this method the writer would consider it preferable, for machines with high windage loss, to the method proposed in the paper, which for this class of machines must be applied with caution.

CALCULATION OF FULL-LOAD TEMPERATURE RISES OF BETWEEN-COIL TEMPERATURE DETECTORS IN ARMATURE, FROM TESTS AT NO EXCITATION, NO-LOAD NORMAL VOLTAGE, AND FULL-LOAD SHORT CIRCUIT FOR A 35,300-KVA, 1,800-RPM TURBINE GENERATOR

| Temperature Rises Above Ingoing Air, Deg C | | | | | | |
|---|---|---|---|---|---|---|
| Temper. detector No. | No excitation (1) | Normal voltage (2) | Short circuit (3) | (2)-(1) +(3) | Total calc. rise at full load | Total rise at full load by test |
| 1 | 9.5 | 20.3 | 42.4 | 53.2 | 54.3 | 53.2 |
| 2 | 9.6 | 20.6 | 33.4 | 44.4 | 45.2 | 45.7 |
| 3 | 11.1 | 27.4 | 28.0 | 44.3 | 45.1 | 41.3 |
| 4 | 10.5 | 21.7 | 37.8 | 49.0 | 49.8 | 48.6 |
| 5 | 10.4 | 21.0 | 38.8 | 49.4 | 50.2 | 52.5 |
| Excitation kw | | 20.1 | 22.6 | | | 76.8 |

$$\text{Additional rise of air at full load} = \frac{1{,}765 \times (76.8 - 20.1 - 22.6)}{\text{cu ft per min.} = 80{,}000} = 0.75°$$

**H. D. Taylor:** This discussion has special reference to the interpretation of no-load tests in making an estimate of full load temperature rise in a-c synchronous machines. There are some complications in the procedure suggested by the author, in that for close results, it seems to be necessary to estimate the temperature rise of the air from the inlet to the middle of the armature teeth for the various test and load conditions; and this involves deducting losses in the core and half the slot depth from total losses.

A somewhat different method, based however on the same principle of superposition has been applied successfully in turbine generator work at Lynn, and seems a little easier to use. The objective is the full-load temperature rise of the armature winding, as shown by standard resistance type temperature detectors. Three no-load runs are made, including the open-circuit and short-circuit runs described by Mr. Fechheimer, and in addition a run at normal speed without excitation. The zero-excitation run gives directly the armature temperature rise due to rotation losses which as Mr. Fechheimer pointed out, are greater in high speed machines such as turbine generators. This quantity subtracted from corresponding readings in the other two runs, gives the additional temperature rise due to voltage losses, and current losses, respectively, *including the additional air temperature rise due to those losses.* The sum of these three values would give the full load temperature rise, except that with the usual system of ventilation, the additional excitation required for full load adds a little more to the air temperature before it reaches the coils and teeth. A small correction is therefore added, which represents the temperature rise of the air due to the difference between full-load excitation loss and the sum of the excitation losses in the open-circuit and short-circuit runs. This is a definite quantity, easily calculated, amounting usually to 2 or 3 deg C, or less.

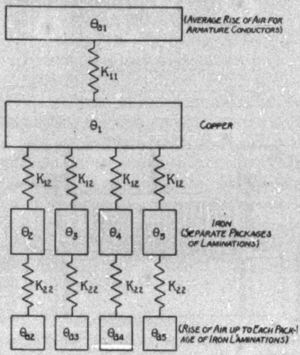

FIG. 3

From a number of cases where no-load runs have been followed by load tests in the shop on the same machine, three examples are given in the following table to illustrate the accuracy of this method.

| Machine | 1 | 2 | 3 |
|---|---|---|---|
| Arm. temp. rise, by resistance temperature detectors, in deg C | | | |
| (1) Due to rotation losses alone | 5.6 | 9.0 | 11.5 |
| (2) Due to "voltage losses" (additional) | 7.2 | 13.7 | 11.5 |
| (3) Due to "current losses" (additional) | 19.5 | 9.7 | 7.4 |
| (4) Correction for full load excitation | 1.8 | 2.8 | 1.8 |
| (5) Expected full load rise, (1) + (2) + (3) + (4) | 34.1 | 35.2 | 32.2 |
| (6) Actual full load rise, by same resistance temperature detectors | 34.5 | 35.6 | 31.2 |

The agreement between the actual load temperature rise and that deduced in this way from no-load runs usually is within 2 deg C.

**E. Weber:** The paper constitutes a valuable method for quick reference in computing the temperature rise in electrical machines. This seems especially desirable considering the recent trend toward economy in the design of electrical machinery. However, several additions appear to be necessary:

1. The thermal problem is a three dimensional problem and therefore can only be roughly approximated by a circuit as shown in Fig. 1 of the paper. It must be kept in mind that $\theta_1$ ad $\theta_2$ vary respectively over the copper and iron volumes.

2. If we assume uniform temperature distribution over the copper and iron in a cross-section of the machine perpendicular to the axis then the relations (5) and (6) hold for any one such cross-section. However, the parameter values $R_{11}R_{12}R_{21}$ and $R_{22}$ will be *different* for each cross-section so that, in applying the relations (5) and (6), the proper values of these parameters must be taken. Obtaining their values from the no-load and short-circuit tests as average values for the whole machine, it is not possible to compare the temperatures thus computed with local temperature measurements in the machines (for example, with thermo couples). This must lead to discrepancies as may be seen in Table I of the paper.

3. The simplifications of the author in the case of no-load and short circuit, putting respectively $P_1 = 0$ and $P_2 = 0$, are not valid in any case. Under no-load conditions there will always be additional losses, such as the no-load copper losses due to the magnetic field variations in the slots and the damper winding losses as well as losses in the end connections. Under short-circuit conditions there will always be additional iron losses due to the higher harmonics of the magnetic field,[2] the so-called surface losses in the poles and additional iron losses due to the local field concentrations. It is, necessaryt herefore, to use the complete relations (5) and (6) for no-load and short-circuit tests, giving

$$\left.\begin{aligned}\theta_{1oc} &= R_{11}P_{1oc} + R_{12}P_{2oc}\\ \theta_{2oc} &= R_{21}P_{1oc} + R_{22}P_{2oc}\end{aligned}\right\} \quad \textbf{(a)}$$

and

$$\left.\begin{aligned}\theta_{1sc} &= R_{11}P_{1sc} + R_{12}P_{2sc}\\ \theta_{2sc} &= R_{21}P_{1sc} + R_{22}P_{2sc}\end{aligned}\right\} \quad \textbf{(b)}$$

These are four equations for the four unknowns $R_{11}$, $R_{12}$, $R_{21}$ and $R_{22}$. The two mutual parameters $R_{12}$ and $R_{21}$ should have the same values, their difference indicating the failure of properly accounting for additional losses. As an example take the two values $R_{21} = 5.6$ and $R_{12} = 6.84$ as given by the author.

Since the total losses often are difficult to measure it may be a sufficient approximation to estimate the additional losses as a percentage of the normal iron and copper losses. The estimations can be based upon experience for the different types of machines.

**C. J. Fechheimer:** At the time that the paper was written it was amazing that many designing engineers still were estimating temperature rises by adding copper and iron losses or omitting the iron losses entirely. The purpose in presenting this paper was fourfold, (1) to call attention to the errors, (2) to offer another simple and approximately correct method, (3) to suggest a means for determining the constants from tests and (4) to propose a fairly accurate method for securing full load temperature rises without going to the expense of making full load tests. These were covered roughly in the *Sibley Journal* article published in 1912, and given as reference 5 in the bibliography In fact the writer started to use the method in 1909.

It is a source of considerable gratification to learn that engineers of the General Electric Company have been using the method in a modified form for a number of years. It is true undoubtedly that equations in the simplified forms as given in the paper can not possibly cover complex heat flow, variable losses, etc., which influence the temperature rise in the steady state. It is questionable how far one should go in introducing corrections, and only those whose effects are of considerable magnitude should be given consideration at all. The practical designing engineer can not take time to employ equations that are greatly involved. The fact that the effect of air temperature rise is not to be ignored, at least not in high speed machines, was appreciated, and recognition of that fact is evidenced from equations (13) to (22) inclusive. Doubtless every engineer has his own way for solving a particular problem, and this is illustrated by Mr. Snell's unique methods for correcting for air temperature rise, which have points of superiority. It is of value to note that if the air temperature rise due to windage loss is negligible, (say less than 0.5 deg C.) the open- and short-circuit temperature rises may be added, without further correction for the air temperature rise due to windage loss. The method suggested by Messrs. Snell and Taylor for taking a third run without excitation is excellent for high speed machines. It is especially gratifying to see how close the calculated and test full load temperature rises agree, the former being obtained by adding the no-load and short-circuit temperature rises and deducting for temperature rise due to "rotational" losses, as given by Messrs. Snell and Taylor for turbine-generators. These and more data of like character would be helpful toward satisfying the designing engineer that further corrections generally are not warranted by the greater complexity in calculation.

Mr. Weber's comments are well taken. It is likely that we are not always justified in assuming that the iron loss is zero on short circuit, but there are very few modern machines in which the variations in magnetic field introduce appreciable loss in the imbedded copper in the slots, although it is no doubt true that the losses in the damper winding bars at no load are not always negligible. Here again the designing engineer should find ways of modifying the general equations to fit his particular problem. If the losses were known with sufficient accuracy, the four equations given by Mr. Weber should be solved for the four unknown thermal resistances, although it is doubtful whether that is worth while, except for extreme cases.

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[2] See *Graphical Determination of Magnetic Fields*, by M. Wieseman, JOURNAL of the A.I.E.E., May 1927, p. 430.

# Parallel Operation of A-C Generators
## Action of Governors and Damper Windings

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THE responsibility for the improper operation of a-c generators in parallel was originally attributed solely to the inconstant action of the prime movers, and later to undesirable generator characteristics, but it is sufficiently clear at the present time that if proper consideration is not given to both elements, unsatisfactory parallel operation will result. The fact, however, that this general problem was first seriously attacked by the electrical engineer has always placed the electrical engineering in a position of criticism when troubles arise, whereas the difficulty very often is as much a mechanical one. One of the purposes of this paper is to demonstrate how closely the two are necessarily interrelated, and that both aspects of the problem must be equally thoroughly investigated.

At the outset, it is in the nature of a clarification of ideas to recognize that the mechanism of generator oscillation is analogous to the torsional oscillation of an inertia through a flexible spring. The influence of a short-circuited winding on the rotor, as shown in Fig. 1b, is to provide mainly a damping action, such as would be analogously obtained by submerging the mechanical system, shown in (a), in a liquid, as in (b). There is an important difference to recognize, however, and that is, that whereas in the mechanical case, the natural period of oscillation of the system is not sensibly changed by immersion (except for the effect of the liquid slightly increasing the rotatory inertia), in the electrical case, depending on the ratio of resistance $R$ to inductive reactance $\omega L$ of the "damper" winding, a sensible effect on the natural period of oscillation may occur due to the introduction of a synchronizing component of torque caused by this oscillation. This effect is discussed later.

The important magnitudes in the mechanical case are the mass moment of inertia, the spring constant (a measure of the torsional flexibility of the spiral spring) and the viscosity of the liquid in which the system is oscillating. In the electrical case, the "flywheel effect" of the rotor plays the same role as the inertia of the mechanical ring.

It is no property of the synchronous machine, *per se*, to exhibit synchronizing torque, *i. e.*, a torque tending to restore the rotor to a position of constant phase with respect to the rotating stator voltage. However, as soon as the machine is coupled in parallel with other generators or an "infinite" power system (terminal voltage constant), synchronizing power flows tending to pull the machine into its proper synchronous position, as soon as it is displaced away from it. This restoring torque can be demonstrated to be proportional to the angular displacement for small angles. However, in stating this, we must assume that during oscillation, the system voltage remains constant, and the excitation is constant as well, otherwise it would not be strictly true that the synchronizing torque could be written as simply proportional to the angle $\theta$.

In all synchronous machines, there exists some tendency to damp out any rotor oscillation around synchronous position because of eddy currents set up mainly in the pole faces, this effect being considerably greater, naturally, for solid poles. However, for all cases where periodic torque disturbances constitute the nature of the application, it has often been deemed desirable to supply a special short-circuited cage winding, the action of which is very similar to that of an induction motor, supplying torque reaction proportional to the velocity of oscillation, $d\theta/dt$, rather than $\theta$, as in the case of synchronizing torque. According to Blondel's two reaction theory, the field of a synchronous machine is considered to be composed of two components: (1) the direct axis field, and (2) the quadrature axis field. The first of the two is considered to have its maximum under a pole, and travels synchronously around the stator—the quadrature axis field is usually very much smaller, and is displaced 90 deg in electrical phase with respect to the direct axis field. Now, with a short-circuited cage winding, there are two types of short-circuit paths: (1) pole-to-pole, and (2) quadrature axis-to-quadrature axis. As the rotor oscillates around its synchronous position, each of the two fields mentioned above react on each of the two types of short-circuit paths mentioned, and four components of torque are set up. For

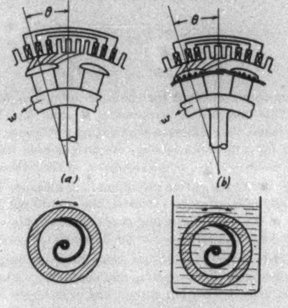

FIG. 1

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

our purpose, however, it is sufficient to consider the action of the pole-to-pole winding on the direct axis field, as shown in Fig. 2, and particularly as it is of the greatest magnitude.

Now consider what happens when the coil, of resistance $R$ and inductance $L$, oscillates with a mechanical frequency $\omega$ around synchronous position. During oscillation, the flux is changing, and generating potential, so that the differential equation of current in the coil can be written as

$$L\frac{di}{dt} + Ri - kB_m\frac{d\theta}{dt} = 0 \qquad (1)$$

where $k$ = constant
$B_m$ = direct axis field strength
$\theta$ = angular displacement
$t$ = time

Within the limits of oscillation $\theta$, since the flux wave is approximately trapezoidal, $B_m$ may be considered constant, without invalidating the strength of the discussion. Now $\theta$ is made up of two parts—a steady part (due to load torque) and a variable part (due to oscillation), *i. e.*, $\theta = \theta_s + \theta_v$, where $\theta_v$ is taken as $\theta_v = \theta_o \sin \omega t$. Substituting the above expression for $\theta$ in (**1**), we obtain

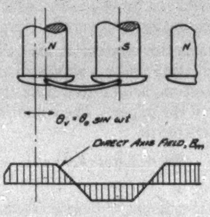

FIG. 2

$$L\frac{di}{dt} + Ri = (kB_m\theta_o\omega)\cos\omega t \qquad (1.1)$$

The solution of (**1.1**) is directly recognized to be

$$i = kB_m\theta_o\left[\frac{\omega R}{R^2+\omega^2L^2}\cos\omega t + \frac{\omega^2 L}{R^2+\omega^2L^2}\sin\omega t\right] \qquad (1.2)$$

Now the torque exerted is proportional to the product of field strength and current, *i. e.*, $T = cB_m i$, so that we have finally

$$T = K\left[\frac{\omega R}{R^2+\omega^2L^2}\cos\omega t + \frac{\omega^2 L}{R^2+\omega^2L^2}\sin\omega t\right] \qquad (1.3)$$

$$= T_{\text{damping}} + T_{\text{synchronizing}}$$

Here, it should be remembered that $\omega$ is the mechanical frequency of oscillation, and $\omega L$ is strictly a motional impedance. The above expression for the damper winding torque can be appreciated physically for, while the voltage in the damper winding is proportional to the velocity $d\theta/dt$, and hence is displaced from the motion by $\pi/2$ in time phase, this is not the case with the current flowing in the damper winding, to which the torque is directly proportional (since the main flux is essentially constant during oscillation), because of further phase displacement due to the inductive reactance in the damper circuit. This accounts for a term in the expression for torque $T$ (equation (**1.3**) ) caused by rotor oscillation which is in phase with the motion, and hence is a synchronizing torque. It is further seen that the maximum value of $T_d$ is $K/2L$, and occurs when $R = \omega L$, which is an often-met relation, and not when $R \to 0$, for in this latter case, the damping component would disappear entirely and the damper winding become entirely ineffective. However, for the more usual installations, the frequencies $\omega$ at which oscillation occurs are such as to keep $\omega L$ small with respect to $R$, so that in practical damper winding design, it is still the aim to reduce $R$ still further. It should be realized that the lower the damper inductance, the more effective it can be made as a damper.

The values of $\omega$ are determined by the frequencies of the sinusoidally varying disturbances. The most common types of disturbance in generator installations are those coming from the variable torque impulses of the prime mover (diesel engine, steam engine, etc.). The frequencies of the disturbances depend on whether, for instance, the driving diesel engine is 2 or 4 cycle, single or double acting, 4, 6, or 8 cylinder, etc.—and disturbances may come from higher harmonics than the first, cases being known where the 4th harmonic has given trouble. For instance, for a 2-cylinder, 4-cycle engine, the lowest frequency would be rotational frequency—for a 6-cylinder, 2-cycle engine, the lowest disturbing frequency would be 6 times rotational frequency, etc. For generator installations of the type being discussed, shaft speeds may vary from 100 to 400 rpm, so that the range of $\omega$ is from less than 2 radians per sec to more than 30 radians per sec. At these higher values, which are the rarer, the value of $\omega L$ becomes important, and too low resistance damper windings are inadmissable. At these higher frequencies, as well, the effect on the synchronizing torque must not be overlooked. In addition to the disturbances coming from the prime mover torque variations, sudden load changes cause the system to oscillate at its natural period—as determined by synchronizing torque and total system inertia—which is usually of the order of 2 or 3 radians per sec, and corresponds to the lower range of the $\omega$'s, discussed above.

The questions relating to proper proportioning of system constants, *i. e.*, flywheels, damper windings, etc., so as to avoid hunting or voltage variation, have been studied in detail by several authors, where the disturbing torques have been periodic forced impulses arising from the prime mover.[1,2,3,4] Another important aspect of the problem of parallel operation, which is fully as vital, but which appears to have been neglected, is the interrelation of governor action and system oscillation. Such cases have been experienced in the past—see Barnes, A.I.E.E. TRANS. Vol. 26, and the like. More recently, Mr. E. A. Tulus, associated with the author, has investigated experimentally such a case, taking complete oscillographic and torsiographic records, and it was as a consequence of this experience that the present investigation was undertaken.

In earlier work, the underlying ideas have been only hazily appreciated, the only guiding principle being that the addition of more damping in the governor and generator system must reduce oscillation, being careful, of course, not to make the governor too sluggish. That the case is complex and requires an accurate quantitative appreciation of the magnitudes involved will be admitted when it is shown, for instance, that the addition of a damper winding to a system having a high governor natural frequency is without point, and the like.

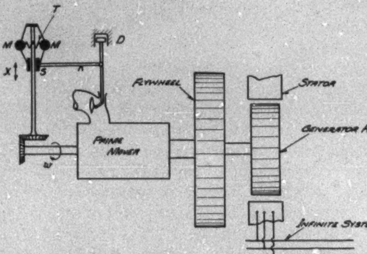

FIG. 3

Let us consider the case of a generator, driven by a reciprocating engine, and governed by direct action, *i. e.*, the inlet valve is directly operated by the governor. The case of indirect governing is analogous, but will be considered in a future paper. It must be appreciated at the outset that even with correctly acting and adjusted governing, there are certain phenomena possible that necessitate closer inspection. Consider the important case when the governor natural frequency (which exists, and is an unavoidable property of the governor) is in the neighborhood of the system natural frequency, as determined by synchronizing torque and total rotating inertia. If a sudden load change takes place, the governor in acting to prevent speed change, passes through a transient condition which is responded to by the now oscillation sensitive generator system, and under unfavorable conditions, the generator oscillation will build up and cause a falling out of step of the generator.

In Fig. 3 is shown schematically a case of an engine driving a generator connected to a large power system, and controlled by a direct acting flyball governor. From a consideration of governor dynamics,[5,6] it can be shown that due to the elastic force exerted by the transverse spring, $T$, an elastic restoring force exists on the sleeve, $S$, against a displacement of the sleeve from its equilibrium position, as determined by the flyballs, $MM$, the geometry of the linkage, the shaft speed $w$ and gear reduction, etc. In the figure, $D$ is an oil dash pot, which provides viscous damping during motion. It is now evident that the governor comprises an oscillatory system which will vibrate freely according to the differential equation of motion written below:

$$m\ddot{x} + c_g\dot{x} + k_gx = 0 \tag{2}$$

where

$m$ = equivalent mass of the governor, referred to translational motion of the sleeve (lb sec$^2$ per in.)
$x$ = translational displacement of sleeve (inches)
$c_g$ = damping constant in governor system, mainly provided by dash pot shown schematically by $D$
$k_g$ = elastic restoring force per unit displacement of sleeve—this is a function of $w$, which changes with the configuration of governor, etc. (lb per in.)

That the generator system is also oscillatory, *i. e.*, capable of oscillating under a simple displacement from equilibrium position, is admitted from the discussion at the beginning of the paper. The condition of free oscillation can be written as

$$I\ddot{\theta} + c_s\dot{\theta} + k_s\theta = 0 \tag{3}$$

where

$I$ = total mass moment of inertia of generator system, *i. e.*, engine inertia + flywheel + generator inertia, etc. (in. lb sec$^2$)
$\theta$ = angular displacement from synchronous position (mechanical radians)
$c_s$ = damping constant, as determined mainly from damper winding design (in. lb per radian per sec)
$k_s$ = synchronizing torque of the generator (in. lb per radian)

Now we must examine and write down analytically how the governor controls the change in speed of the generator system under load changes—and how the oscillations may be excited in the generator system, *i. e.*, how equations (**2**) and (**3**) are interconnected.

Since the governor position is determined by the rotational speed of its spindle, the displacement $x$ of the governor sleeve must be connected in some way with the shaft speed $w$ (since generator shaft and governor spindle are rigidly connected by a gear). For small changes in speed, $\Delta w$, it can be shown to be true that the position of the sleeve changes proportionately, and further, that as the speed increases, $x$ decreases. Further, since the governor sleeve is connected rigidly through a linkage to the power inlet valve of the prime mover, a change in load of the machine (which means a proportionate change in torque, $\Delta T$, since the change in

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1. For references see Bibliography.

speed is small) is a linear function of the sleeve displacement, *i. e.*, $\Delta T \propto x$. Besides a sudden change in shaft torque, $\Delta T$, mentioned above, there exists the periodic disturbing torque originating in the prime mover, the purely oscillatory part of which may be written as $T_o$ sin $\omega t$, so that our equations of motion describing the phenomena are

$$\left.\begin{aligned} I\ddot{\theta} + c_s\dot{\theta} + k_s\theta &= \Delta T + T_o \sin \omega t \\ m\ddot{x} + c_g\dot{x} + k_g x &= -c\,(\Delta w) \end{aligned}\right\} \qquad (4)$$

where

$$\left.\begin{aligned} \Delta T &= kx \\ \Delta w &= \dot{\theta} \end{aligned}\right\} \qquad (5)$$

Equation (**5b**) is merely an identity. By introducing (**5**) into (**4**), we get

$$\left.\begin{aligned} I\ddot{\theta} + c_s\dot{\theta} + k_s\theta &= kx + T_o \sin \omega t \\ m\ddot{x} + c_g\dot{x} + k_g x &= -c\dot{\theta} \end{aligned}\right\} \qquad (6)$$

It is important to discuss for the moment the significance of the constants $k$ and $c$, since the two are tied up with the governor sensitivity and design. If we call the maximum travel of the governor sleeve permitted by the design, $x_{max}$, and this distance be transversed in a speed change of $\Delta w_{max}$, which change results in a force on the governor sleeve of $k_g x_{max}$, then $c$ is defined as

$$c = \frac{k_g \, . \, x_{max}}{\Delta w} = \frac{k_g \, . \, x_{max}}{w \, . \, \dfrac{\Delta w}{w}}$$

$$= \frac{k_g \, . \, x_{max}}{w \, . \, \delta}$$

where $\delta$ is the regulation of the governor, and is of the order of 3 per cent. Concerning $k$, if it is taken that the maximum travel of the governor sleeve $x_{max}$ corresponds to full action of the inlet valve, *i. e.*, from closed to open position, and $T_{nor.}$ is the normal full load torque, then

$$k = T_{nor.}/x_{max}$$

Reverting to equations (**6**), it is seen that if our governor were an "ideal" one, *i. e.*, without mass or friction, then our relations would be

$$\left.\begin{aligned} & I\ddot{\theta} + c_s\dot{\theta} + k_s\theta - kx = T_o \sin \omega t \\ \text{and} \quad & k_g x = -c\dot{\theta} \quad \text{or} \quad x = -c/k_g\dot{\theta} \end{aligned}\right\} \qquad (7)$$

Substituting (**7b**) in (**7a**) gives

$$I\ddot{\theta} + (c_s + k/k_g c)\,\dot{\theta} + k_s\theta = T_o \sin \omega t \qquad (8)$$

It is clear from (**8**) that ideally, governor action is the equivalent of pure damping, *i. e.*, a governor, as concerns torsional oscillation, furnishes a means of introducing damping.* If, however, the motion $x$ were not exactly out of phase with the generator oscillation (as indicated by (**7b**) ), as might be caused by inertia or damping delay in the governor system, it is even conceivable that the action of the governor might become detrimental. The consideration of just these conditions is our problem, and follows from a solution of the coupled equation (**6**).

Since we are not interested for the moment in the motion under the impressed oscillatory torque from the engine, but rather the interaction of governor and generator, we must consider the solution of

$$\left.\begin{aligned} I\ddot{\theta} + c_s\dot{\theta} + k_s\theta &= kx \\ m\ddot{x} + c_g\dot{x} + k_g x &= -c\dot{\theta} \end{aligned}\right\} \qquad (9)$$

Introducing the type solutions

$$\left.\begin{aligned} x &= Xe^{\alpha t} \\ \theta &= \Theta e^{\alpha t} \end{aligned}\right\} \qquad (10)$$

By substituting (**10**) in (**9**), we obtain as the equation of compatibility a limitation on the $\alpha$'s as determined by the 4th degree algebraic equation:

$$\alpha^4 + \alpha^3\left[\frac{c_s}{I} + \frac{c_g}{m}\right] + \alpha^2\left[\frac{k_s}{I} + \frac{k_g}{m} + \frac{c_s}{I} \cdot \frac{c_g}{m}\right]$$

$$+ \alpha\left[\frac{c_g}{m} \cdot \frac{k_s}{I} + \frac{c_s}{I} \cdot \frac{k_g}{m} + \frac{ck}{Im}\right]$$

$$+ \left[\frac{k_g}{m} \cdot \frac{k_s}{I}\right] = 0 \qquad (11)$$

This equation is of the type

$$\alpha^4 + C_1\alpha^3 + C_2\alpha^2 + C_3\alpha + C_4 = 0 \qquad (12)$$

and thus it follows that there are four values of $\alpha$. Since all the coefficients, $C_1 \ldots C_4$, are real and positive, it follows that the roots of such an algebraic equation are also either real or conjugate complex. Since, however, we recognize that the uncoupled systems are oscillatory, a decent assumption to make is that our coupled system is oscillatory as well, so that all our roots will be assumed at first to be complex:

$$\left.\begin{aligned} \alpha_1 &= p' + iq' \\ \alpha_2 &= p' - iq' \\ \alpha_3 &= r' + is' \\ \alpha_4 &= r' - is' \end{aligned}\right\} \qquad (13)$$

If there exist any real roots, then either the $q$'s or the $s$'s will be imaginary or zero. When the $\alpha$'s are determined, the final solutions are then

$$\left.\begin{aligned} x &= \sum_{n=1}^{4} X_n e^{\alpha_n t} \\ \theta &= \sum_{n=1}^{4} \Theta_n \, e^{\alpha_n t} \end{aligned}\right\} \qquad (14)$$

where, however, the $X_n$'s and the $\Theta_n$'s are not independent, there being only 4 integration constants. Now by introducing (**13**) into (**14**) and recognizing that

$$\begin{aligned} X_1 e^{\alpha_1 t} + X_2 e^{\alpha_2 t} &= e^{p't}\,[X_1' \sin q't + X_2' \cos q't] \\ &= e^{p't}\,[X_{\mathrm{I}} \sin (q't + \epsilon_{1x})] \end{aligned}$$

the solution (**14**) takes on the physically more real form of

$$\left.\begin{aligned} x &= X_{\mathrm{I}} e^{p't} \sin (q't + \epsilon_{1x}) + X_{\mathrm{II}} e^{r't} \sin (s't + \epsilon_{2x}) \\ \theta &= \Theta_{\mathrm{I}} e^{p't} \sin (q't + \epsilon_{1\theta}) + \Theta_{\mathrm{II}} e^{r't} \sin (s't + \epsilon_{2\theta}) \end{aligned}\right\} \qquad (15)$$

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*Schenkel has called attention to this point of view, *loc. cit.*

This form tells us immediately that our motions during coupled action of the generator and governor (without external disturbance from the engine) are oscillatory with two distinct frequencies, each damped according to different decrements. We now may realize for the first time that the condition of governor stability, *i. e.*, condition under which all oscillations decay with time, requires that both $p'$ and $r'$ be negative. If either $p'$ or $r'$ be positive, then the corresponding oscillations increase with time, and the generator will fall out of step after a few oscillations.

The determination of the amplitudes, $X$ and $\Theta$, the phase angles $\epsilon$, the damping constants $p'$ and $r'$, and the frequencies $q'$ and $s'$ constitute the complete solution of our problem. As the amplitudes and phase angles are determined by the initial conditions, and offer no notion of the stability of action, we are not concerned for the time being. We are, however, immediately concerned with the determination of the values of $p'$, $q'$, $r'$, and $s'$. From a theorem in the Theory of Algebraic Equations, it is known for quartic equations that the sum of the roots equals the negative of the coefficient of the cubic term (in equation (**12**), for instance); the sum of the products of the roots taken two at a time equals the coefficient of the quadratic term; the sum of the products, taken three at a time, equals the negative of the coefficient of the linear term; and the product of the roots equals the constant term. This gives us four equations to determine the four roots $\alpha_1 \ldots \alpha_4$. By writing down these relations, we obtain the equations:

$$\left.\begin{aligned} p' + r' &= -C_{1/2} \\ p'^2 + q'^2 + r'^2 + s'^2 + 4p'r' &= C_2 \\ r'(p'^2 + q'^2) + p'(r'^2 + s'^2) &= -C_{3/2} \\ (p'^2 + q'^2)(r'^2 + s'^2) &= C_4 \end{aligned}\right\} \quad (\mathbf{16})$$

Now, the constants $C_1 \ldots C_4$ in (**16**) are to be taken from equations (**11**), but it is desirable to notice here that, for the uncoupled systems

$$\left.\begin{aligned} p &= -\frac{c_s}{2I} \\ r &= -\frac{c_g}{2m} \\ p^2 + q^2 &= \frac{k_s}{I} = \omega_s^2 \\ r^2 + s^2 &= \frac{k_g}{m} = \omega_g^2 \end{aligned}\right\} \quad (\mathbf{17})$$

so that (**16**) finally becomes

$$\left.\begin{aligned} p' + r' &= p + r \\ \omega_1^2 + \omega_2^2 + 4p'r' &= \omega_s^2 + \omega_g^2 + 4pr \\ r'\omega_1^2 + p'\omega_2^2 &= r\omega_s^2 + p\omega_g^2 - \gamma \\ \omega_1^2 \cdot \omega_2^2 &= \omega_s^2 \cdot \omega_g^2 \end{aligned}\right\} \quad (\mathbf{18})$$

where $\omega_1^2 = p'^2 + q'^2$; $\omega_2^2 = r'^2 + s'^2$; and

$$\gamma = \frac{ck}{2Im} = \frac{k_g \cdot x_{max}}{\delta w} \cdot \frac{T_n}{x_{max}} \cdot \frac{1}{2Im} = \frac{\omega_g^2}{2\delta\tau} \quad (\mathbf{19})$$

where $\tau$ = time to bring the total generator system to full speed from standstill, under full load torque.

These are a remarkably symmetrical set of equations, and command attention. It is now evident why the $p$'s and $q$'s were primed in (**13**)—the primed values refer to the coupled system, while the unprimed, to the uncoupled. Equations (**18**) give us fully and exactly the relations between the new frequencies and damping constants, $p'$, $q'$, $r'$ and $s'$ in terms of the old, $p$, $q$, $r$ and $s$—as affected by the magnitude of

$$\gamma = \frac{\omega_g^2}{2\delta\tau},$$

which indicates the efficacy of the governing. For this reason, $\gamma$ must be called the "characteristic constant" of the combined generator and governor system, and is analogous to a coupling term.

Equation (**18**) furnishes us with four equations to determine four unknowns—which equations, however, are non-linear, and put us to considerable complexity to solve. Let us take advantage, however, of our physical concepts to attack the problem of stability directly. Referring to equation (**18**), by extracting the square root of (**18d**) and adding 2 times the result, to (**18b**), we obtain

$$(\omega_1 + \omega_2)^2 + 4p'r' = (\omega_s + \omega_g)^2 + 4pr \quad (\mathbf{20})$$

Repeating, but this time subtracting,

$$(\omega_1 - \omega_2)^2 + 4p'r' = (\omega_s - \omega_g)^2 + 4pr \quad (\mathbf{21})$$

Now, equation (**20**) may be written as

$$\omega_1 + \omega_2 = \sqrt{(\omega_s + \omega_g)^2 + 4(pr - p'r')} \quad (\mathbf{22})$$

and, likewise, (**21**) as

$$\omega_1 - \omega_2 = \sqrt{(\omega_s - \omega_g)^2 + 4(pr - p'r')} \quad (\mathbf{23})$$

The positive square root is always meant, and it is arbitrarily assumed that $\omega_1 > \omega_2$. From (**22**) and (**23**), we get expressions for the $\omega$'s, by elimination:

$$\begin{aligned} \omega_1 &= \frac{1}{2}\sqrt{(\omega_s + \omega_g)^2 + 4(pr - p'r')} \\ &\quad + \frac{1}{2}\sqrt{(\omega_s - \omega_g)^2 + 4(pr - p'r')} \\ \omega_2 &= \frac{1}{2}\sqrt{(\omega_s + \omega_g)^2 + 4(pr - p'r')} \\ &\quad - \frac{1}{2}\sqrt{(\omega_s - \omega_g)^2 + 4(pr - p'r')} \end{aligned} \quad (\mathbf{24})$$

Now, by multiplying (**18a**) by $\omega_1^2$ and eliminating between the result and (**18c**), we get for $p'$:

$$p' = \frac{(p + r)\,\omega_1^2 - (r\omega_s^2 + p\omega_g^2 - \gamma)}{\omega_1^2 - \omega_2^2} \qquad (25)$$

As was discussed earlier, stability of governing is indicated by having both $p'$ and $r' < o$. Now, from an examination of (**18a**), it is seen that if there were no damping in either the governor or generator systems, *i. e.*, $p = r = o$, then it would be impossible to have stable operation, since $p'$ would equal $- r' \neq o$, because of (**18c**). We thus observe that it is imperative to have damping in either the generator or the governor system (not necessarily both) to begin with. It is more usual to provide this damping in the governor system, by introduction of dash pots or the like. In general, however, with both $p$ and $r \neq o$ (both being actually negative quantities), we must now follow the force of the argument presented by considering the border-line case, $p' = o$. For $p' = o$, $r'$ must be negative, from relation (**18a**), since both $p$ and $r$ are negative; so that whereas the amplitudes of one type of oscillation would continue undiminished, the other would die away—and the condition would be called stable. Now, for $p'$ slightly $< o$, $r'$ would still remain $< o$, and stability in its real sense would be established.

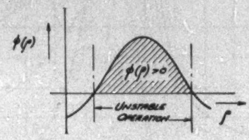

FIG. 4

We are interested then in determining what conditions are necessary to make $p' = o$. By placing $p' = o$ in (**22**) . . . (**24**), and writing

$$\left.\begin{aligned} \Delta_1 &= (\omega_s + \omega_g)^2 + 4\,pr \\ \Delta_2 &= (\omega_s - \omega_g)^2 + 4\,pr \\ \Delta_3 &= \left( r\omega_s^2 + p\omega_g^2 - \frac{\omega_g^2}{2\,\delta\tau} \right) \end{aligned}\right\} \qquad (26)$$

We have from (**24a**) by squaring

$$\omega_1^2 = \frac{1}{4}\left(\Delta_1 + \Delta_2 + 2\sqrt{\Delta_1\Delta_2}\right) \qquad (27)$$

Repeating for (**24b**) and subtracting from (**27**) above, we get

$$\omega_1^2 - \omega_2^2 = \sqrt{\Delta_1\Delta_2} \qquad (28)$$

By substituting (**26c**), (**27**), and (**28**) in (**25**), at the same time recognizing that $p' < o$, we get

$$0 > \frac{\left(\dfrac{p + n}{4}\right)(\Delta_1 + \Delta_2 + 2\sqrt{\Delta_1\Delta_2}) - \Delta_3}{\sqrt{\Delta_1\Delta_2}} \qquad (29)$$

as the *criterion of stability*.

Expanding (**29**) by introducing the expanded values of the Δ's from (**26**), we get

$$\frac{\omega_g^2\left(\dfrac{1}{2\,\delta\tau} - p\right) - r\omega_s^2 + \dfrac{p + r}{2}\{\,\omega_s^2 + \omega_g^2 + 4pr + \sqrt{(\omega_s^2 - \omega_g^2)^2 + 8\,pr\,(\omega_s^2 + \omega_g^2) + 16\,p^2r^2}\,\}}{\sqrt{(\omega_s^2 - \omega_g^2 + 8\,pr\,(\omega_s^2 + \omega_g^2) + 16\,p^2r^2}} < 0 \qquad (30)$$

By denoting

$$\frac{\omega_g}{\omega_s} = \rho,$$

equation (**30**) may be written as

$$\frac{\omega_s^2\rho^2\left(\dfrac{1}{2\,\delta\tau} - p\right) - r\,\omega_s^2 + \dfrac{p + r}{2}\{\,\omega_s^2(1+\rho^2) + 4pr + \sqrt{\omega_s^4(1-\rho^2)^2 + 8pr\,\omega_s^2(1+\rho^2) + 16p^2r^2}\,\}}{\sqrt{\omega_s^4\,(1 - \rho^2)^2 + 8\,pr\,\omega_s^2\,(1 + \rho^2) + 16\,p^2r^2}} < 0 \qquad (31)$$

The case of *isochronism*, *i. e.*, when the natural periods of the governor and generator systems coincide, is given by $\rho = 1$ ($\omega_s = \omega_g = \omega$). Thus, (**31**) becomes somewhat simpler

$$\frac{\dfrac{\omega^2}{2\,\delta\tau} + 2\,(p + r)\,(pr + \sqrt{pr\,(pr + \omega^2)}\,)}{4\sqrt{pr\,(pr + \omega^2)}} < 0 \qquad (32)$$

It is immediately recognizable from (**32**), however, that since $\omega^2/2\,\delta\tau > o$, it is imperative that *both* governor damping and generator damping exist, in order to obtain stability. This means that a damper winding is imperative where isochronism has unfortunately been found to be the case, unless the governor natural frequency or generator natural frequency can be sufficiently altered. The above condition should be contrasted with the conditions $\rho < 1$ and $\rho > 1$, where only $p$ or $r$ need exist—not necessarily both.

An appreciation of the general problem can only be had by numerically interpreting equation (**31**)—varying $\rho$, $p$, and $r$ for a fixed value of $\omega_s$ as reference, for instance. A usual value of $\omega_s = 20$ radians per sec ($\simeq 200$ vibrations per minute) will be taken. By assuming $p = r = o, - 0.5, - 1.0, - 2.0 - 3.0$, and $p = - 0.2$ and $r = - 2.0$—and keeping $\rho$ as the independent variable, we can write (**31**) as

$$p' = \phi(\rho) < o, \text{ and plot } \phi(\rho) \textit{ vs. } \rho$$

obtaining a curve of the type shown. Taking advantage of a knowledge of the usual magnitudes of the quantities involved, equation (**31**) may be greatly simplified and reveal its fundamental significance more clearly. For

$w_s \simeq 20$ radians per sec
$\delta \simeq 3$ per cent
$\tau \simeq 11$ sec
$p \simeq r \simeq - 1.0$

we see that (**31**) has three simplified forms, depending on whether $\rho > 1$, $\rho = 1$, or $\rho < 1$. The cases $\rho \gtrless 1$

must be excluded from the region $0.8 < \rho < 1.2$. For $\rho > 1$, (**31**) reduces to

$$\frac{\left(\frac{1}{2\,\delta\tau} + r\right)\rho^2 - r}{\rho^2 - 1} < 0 \tag{33}$$

Similarly, we get for $\rho < 1$

$$\frac{\left(\frac{1}{2\,\delta\tau} - p\right)\rho^2 + p}{1 - \rho^2} < 0 \tag{34}$$

For $\rho = 1$, (**32**) simplifies to

$$\frac{\omega}{8\,\delta\tau\,\sqrt{pr}} + \frac{p + r}{2} < 0 \tag{35}$$

Equations (**33**), (**34**), and (**35**) describe the essentials of the entire stability considerations. It is clear that:

1. If the governor natural frequency exceeds that of the generator system, that large governor damping is necessary to produce stability.
2. If the governor natural frequency is less than the generator natural frequency, then a damper winding is imperative.
3. If isochronism exists, both governor and generator must have damping, and to a very much larger degree than in either (**1**) or (**2**).

In Fig. 5 are shown the various cases plotted that are discussed in the previous paragraphs. For the cases taken, it is seen that stable operation is even possible at isochronism, provided a damper winding with a damping constant $p = -3.0$ is provided, as well as an equally well damped governor. That such a damper is possible is realized when it can be stated that it is possible to make dampers with a specific damping torque (in inch—lb per mechanical radians per sec) equal to more than 1½ per cent of the specific synchronizing torque (in lb per radian), *i. e.*,

$$|2\,p| = 1.5\%\ w_s^2, \text{ or in this case}$$

$$p = -\frac{0.015}{2} \times (20)^2 = -3.0$$

In order to crystallize the ideas involved, consider their application to an actual installation. Consider two 250-rpm, 4,000-kw generators, driven by triple-expansion steam engines, running in parallel. The additional magnitudes involved are

Total system inertia $= I = 200{,}000$ in lb. sec²
System time constant $= \tau = 5$ sec
Synchronizing torque $= k_s = 6.0 \times 10^7$ in per radian
Hunting frequency $= w_s = k_s/I = 17.3$ radians per sec (166 per min)
Governor natural frequency $= w_g = 13.6$ radians per sec (130 per min)
Ratio $w_g/w_s$ $= \rho = 0.78$
Regulation $= \delta = 8\%$
Generator damping $= c_s = .0.01 \times 10^7$ in lb per radian per sec

Generator damping exponent $= p = -\dfrac{c_s}{2\,I} = -0.25$

Governor damping exponent $= r = -3.0$

Assuming the two generators are alike, then the paralleling relations are the same as those for one of the generators paralleling with an infinite system. It is first observed that both the governor and generator natural frequencies are far enough removed from the operating speed, 250 rpm (and multiples of the same, *i. e.*, 3 × 250, etc.) that no disturbances of the ordinary type will be encountered. It should be realized that coincidence of prime mover torque harmonics with governor natural frequency is just as serious as with generator natural frequency.

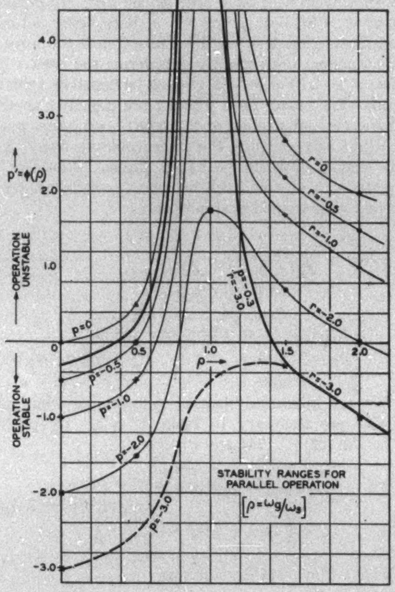

FIG. 5

We are concerned now with the stability conditions under sudden load changes. These are determined from equation (**34**), where $\rho = 0.78$, which is $< 1$. The value of the expression in (**34**) is

$$\frac{\left(\frac{1}{2\ \delta\tau}-p\right)\rho^2\ +\ p}{1-\rho^2}=\frac{\left(\frac{1}{2\times0.08\times5}+0.25\right)(0.78)^2-0.25}{1-(0.78)^2}$$

$$=\frac{(1.50)\ (0.61)-(0.25)}{0.39}=+\ 1.70,\text{ which is }>o.$$

This shows that the condition is unstable, and that the generators would fall apart. It is also evident from (**34**), that governor damping plays no role in the stability conditions for the case in question. Referring to equation (**34**) again, we have the option of decreasing the flywheel size, thus still further reducing $\rho$, but this will be attended by an objectionable increase in speed fluctuation due to prime mover torque variations, as well as an undesirable decrease in the time constant $\tau$. It is possible to redesign the governor to give a much lower natural period—in this case $\rho$ would have to be reduced to 0.40, which would mean $w_g$ = 6.9 radians per sec (67 per min). The other alternative is to add a low resistance damper winding, which will give us a new value of $c_s = 0.10 \times 10^7$ in lb per radian per sec ($c_s = 1\ 2/3\%$ of $k_s$), and make $p = -\ 2.50$. This would result in

$$\frac{\left(\frac{1}{2\times0.08\times5}+2.50\right)(0.78)^2-2.50}{1-(0.78)^2}$$

$$=-\ 0.54,\text{ which is }<o$$

and the operation would be stable.

The conclusions that we obtain from this investigation are that whereas prime mover torque impulses must not coincide with either generator or governor natural frequencies for satisfactory continuous parallel operation—that certain relations must exist between the governor and generator oscillatory systems for stability under rapid load changes, such as are obtained at the moment of synchronizing or under power load assumption. This condition of stability, as expressed in equation (**31**), indicates that:

1. When the governor natural frequency exceeds the generator natural frequency, damping in the governor is necessary, and useless in the generator.

2. When the governor natural frequency is less than generator natural frequency, a damper winding is necessary, and governor damping is without point.

3. For isochronism, both generator and governor damping are necessary, and in large amounts.

For systems using indirect governing, *i.e.*, through the use of a servomotor, such as are necessary for waterwheel and turbine generator installations, unless very rapid response servomotors are used, phenomena as discussed in this paper do not exhibit themselves.

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## Discussion

**J. P. Den Hartog:** The analysis of the instability problem starting from the differential equations (**6**) until the four algebraic equations (**16**) is entirely clear and straightforward. From there on, however, the argument is difficult to follow. In solving the equations (**16**) the author draws square roots of which only the + − signs are retained, then adds and subtracts: a procedure that is just as likely to give correct as incorrect results. Moreover, until equation (**25**) the author keeps $p' \neq 0$, then makes it zero and substitutes again into (**25**). The final result (**31**), (and the equations (**33**) and (**34**) as well) appear in the form of a fraction with an inherently positive denominator, which does not affect the sign and consequently should be omitted for the sake of simplicity.

A much simpler and more convincing derivation of the result (**31**) is given on page 628 of Tolle's book (2nd edition, 1909), quoted by the author[5]. It is as follows: We want to know under which conditions $p'$ (or $r'$) is positive. When $p'$ is zero it is evident that we are on a *boundary* between $p'$ being positive and negative. Set $p' = 0$ immediately in (**16**):

$$\left.\begin{aligned} r' &= -\ C_1/2\\ q'^2+r'^2+s'^2 &= C_2\\ r'q'^2 &= -\ C_3/2\\ q'^2\,(r'^2+s'^2) &= C_4 \end{aligned}\right\}\qquad(\mathbf{a})$$

These are four equations in the three unknowns, $q'$, $r'$, $s'$, which are eliminated in the following manner.

From the second equation (**a**) solve $r'^2 + s'^2$ and substitute into the fourth:

$$q'^2\,(C_2-q'^2)=C_4$$

Solve $q'^2$ from the third and substitute into the above:

$$-\frac{C_3}{2r'}\left(C_2+\frac{C_3}{2r'}\right)=C_4$$

Finally take the value of $r'$ from the first equation (**a**) and substitute:

$$\frac{C_3}{C_1}\left(C_2-\frac{C_3}{C_1}\right)=C_4$$

or:

$$C_1C_2C_3=C_3^2+C_1^2C_4\qquad(\mathbf{b})$$

which is Tolle's equation (**207**).

This is the relation necessary in order that $p'$ be zero. Since (**16**) is symmetrical with respect to $p'$ and $r'$, the relation of $r' = 0$ also is expressed by (**b**), which thus is the necessary and sufficient relation between the $C$'s in order to have the system on the boundary between stability and instability.

When the values for $C_1$, $C_2$, $C_3$ and $C_4$, as shown in equations (**10**) and (**11**) are substituted into (**b**), we obtain with Mr. Stone's notations:

$$(p+r)\ \{\ \omega_s^2\,(1+\rho^2)+4\,pr\ \}\ .\ \left\{\ p-\frac{1}{2\delta\tau}+\frac{r}{\rho^2}\ \right\}$$

$$=\omega_s^2\,(p+r)^2+\rho^2\omega_s^2\left\{\ p-\frac{1}{2\delta\tau}+\frac{r}{\rho^2}\ \right\}^2=0\qquad(\mathbf{c})$$

which is the same result as the numerator of (**31**) after elimination of its square root.

The equations (**c**) or (**31**) express a relation between *four* independent variables:

(1) The generator damping $p$.
(2) The governor damping $r$.
(3) The frequency ratio $\rho$.
(4) The "coupling constant" $\delta\tau$.

In Fig. 5 a fifth variable $p' = \phi(\rho)$ is brought in and the relation between these *five* is plotted as a single family of curves. This obviously is impossible; a diagram like Fig. 5 can represent only the relations between *three* variables. In this case, however, it is said that for $\rho < 1$ the stability is independent of generator damping. But the value of the "coupling constant" $\delta\tau$ or $\gamma$ is not mentioned at all.

Moreover, for a graphical representation of the result (**c**) it is essential to use *dimensionless variables* in order to make the diagrams applicable to all *possible cases*.

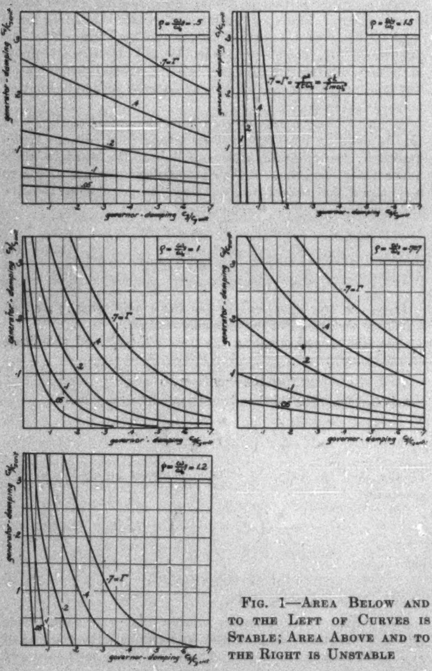

FIG. 1—AREA BELOW AND TO THE LEFT OF CURVES IS STABLE; AREA ABOVE AND TO THE RIGHT IS UNSTABLE

Mr. Stone's variables $p$ and $r$ are of the dimension 1/time, while $\delta\tau$ is of the dimension of time directly. In order to make these dimensionless, it is convenient to introduce the "critical damping coefficients."

For the governor we have:

$$(c_g)_{crit} = 2m\omega_g,$$

which is the damping necessary to make the governor just dead beat. Thus the four new dimensionless variables are:

$$c_g/c_{g\,crit} = \frac{c_g}{2m\omega_g} = \text{governor damping ratio}$$

$$c_s/c_{s\,crit} = \frac{c_s}{2I\omega_s} = \text{generator damping ratio}$$

$$\rho = \omega_g/\omega_s = \text{frequency ratio}$$

$$\Gamma = \frac{ck}{Im\omega_s^3} = \frac{2\gamma}{\omega_s^3} = \frac{\rho^2}{\delta\tau\omega_s} = \text{coupling ratio}$$

Writing the constants $C_1$, etc., of equations (**11**) and (**12**) in terms of these dimensionless variables and entering with them into (**b**) leads to:

$$ab + a^2b^2 + ab^2 + ab\rho^2 + a^2b\rho + a^2b^2\rho + \Gamma(a + b\rho + a^2b + ab^2)$$
$$= \Gamma(\Gamma + b + a\rho) + 2ab\rho \qquad (\mathbf{d})$$

where:

$$a = 2\frac{c_s}{c_{s\,crit}} \text{ and } b = 2\rho\frac{c_g}{c_{g\,crit}}.$$

This complicated equation is the same as (**31**) or (**c**), but written in a dimensionless form. Since there are four variables, the relation can be plotted only as a set of diagrams, each containing a family of curves.

This is shown in Fig. 1. The two damping ratios are measured vertically and horizontally along the axes; the coupling ratio $\Gamma$ is the parameter for the various curves, while for each frequency ratio $\rho$ there is another diagram.

It is remembered that each curve in these figures represents the relation (**b**) which is the boundary between stability and instability. *The analysis has not revealed on which side of each curve the system is stable.* This has to be found by trying out one case numerically, or as follows:

Right under (**25**) Mr. Stone draws the conclusion that at $p = r = 0$ (or in the new notation at $c_g/c_{g\,crit} = c_s/c_{s\,crit} = 0$) the system is *unstable*. Thus we see that the area *under and to the left* of each curve of Fig. 1 represents *instability*; the area above is stable.

The diagrams of Fig. 1 give the solution completely. As an example take the numerical case Mr. Stone discusses, for which the four dimensionless variables become:

$$(c/c_{crit})_{gen} = 0.014 \qquad (c/c_{crit})_{gov} = 0.22$$
$$\rho = 0.78 \qquad \Gamma = 0.085$$

Taking the governor damping 0.22 and the frequency ratio $\rho = 0.5$, we find from the first diagram by interpolation of $\Gamma = 0.085$ between $\Gamma = 0.05$ and $\Gamma = 0.10$, that a generator damping of 0.045 is necessary to make the system stable. For $\rho = 0.707$ similarly we find that 0.055 is needed and for the resonance case $\rho = 1$ the required generator damping ratio is 0.026. Plotting the three values 0.045, 0.055 and 0.026 on a rough sketch we can interpolate graphically for the required frequency $\rho = 0.78$ and find that about 0.050 generator damping is required for stability.

The first two of the three conclusions of the paper are entirely correct, but the last one is inaccurate in one respect. It is seen that the required damping at "resonance" $\rho = 1$ is *not* larger than away from $\rho = 1$. In the numerical case cited by Mr. Stone *the required generator damping for stability in the "resonance" case* ($\rho = 1$) *would be about half as great as in the actual case of* $\rho = 0.78$, as was seen above.

The author calculates the stability of the system in each case from either (**33**) or (**34**) as the case may be and it is stated that these are obtained from (**31**) by letting $\rho$ be $\lesseqgtr 1$. It would be desirable if the author would explain this in some more detail, since the results are not at all obvious.

With the diagrams of Fig. 1 the significance of the solutions (**33**) and (**34**) becomes apparent. Briefly, formula (**33**) states that for $\rho > 1$ the curves of Fig. 1 are straight vertical lines with the correct intersections at the governor damping axis, and similarly (**34**) gives horizontal lines for $\rho < 1$. Consequently (**33**) and (**34**) are excellent approximations for small values of the damping.

In conclusion it is of interest to note that, although this problem was solved nearly completely in 1902 by Föppl,[1] and has subsequently appeared in a number of classical German text books,[2] apparently no mention has ever been made of it in the English or American literature.

**W. H. Ingram:** Routh in his Adams Prize Essay at the University of Cambridge for the year 1877 discussed the stability of the Watt governor and found that its motion was described by a third order differential equation. He found also that the dash-pot friction must not be small, so it would hardly be safe to assume that two of the roots are conjugate complex.

General criteria of stability were also given; *vide* "On the Stability of a Given State of Motion," MacMillan, p. 29. A practical treatment of the problem of governor controlled generators is given in Juillard's "Die Selbsttaetige Regelung Elektrischer Maschinen."

**T. A. Rogers:** There was one point brought to the writer's attention while going over the paper that is discussed in the following.

Solving equation (1.1) we get for the complete solution

$$i = K_1 E^{-\frac{R}{L}t} + kB_m\theta_o\left[\frac{\omega R}{R^2+\omega^2L^2}\cos\omega t + \frac{\omega^2 L}{R^2+\omega^2L^2}\sin\omega t\right]$$

The term $K_1 E^{-\frac{R}{L}}$ is omitted in equation (1.2). Was it omitted because the paper discusses steady state oscillations only or because the decrement is high and the term becomes negligible after a very short time? It would seem that if a sudden displacement of the rotor were introduced, this term would act as an additional damping torque and for the first instant might not be negligible.

It might be pointed out also that the decrement $R/L$ is proportional to $1/T_q''$ where $T_q''$ is the quadrature axis sub-transient short-circuit time constant as defined in the "Report of the Subject Committee on Proposed Definitions of Terms Used in Power Systems" Section 4, paragraph 21. The writer has never seen values of this time constant published but assumes that it is of the order of magnitude of $T_d''$ which is quite small. In this case the transient term $K_1 E^{-\frac{R}{L}t}$ would become negligible after a very short time and may be disregarded altogether.

An additional oscillating system which may introduce stability problems in governing lies in the mechanical system consisting of the prime-mover, shaft, flywheel and generator. In some cases the torsional oscillation of this system may coincide with the harmonic of the prime mover torque, or with the free period of the governor and may introduce hunting of the prime mover under light-load and no-load conditions.

**M. Stone:** Professor Den Hartog's interesting discussion is answered in the following:

The objection to using the + sign in extracting the square roots disappears when the convention is adhered to that $\omega_2 > \omega_1$, as has been done. The reason for retaining the denominator in the inequality (31) is to obtain a more accurate idea of the proximity to the limit of stability, and the importance of governor and generator damping. These are plotted in Fig. 5. Professor Den Hartog states that equation (31) is derived in Tolle's book, but this is not the case, since he does not consider the case of this paper, of which (31) is the criterion. Probably what is referred to are the conditions for stability for a general 4th degree algebraic equation, such as (11) is, and which (12) typifies. The author does not claim to be the first to study this general mathematical question, which it is believed Hurwitz in a *Mathematische Annalen* publication in the 1870's first discussed. The author's development of the stability criterion in this case has been from as physical an idea as the case affords.

Although Professor Den Hartog states that his equation (c) is the same as the author's (31), I am not able to follow the development. At any rate, the omission of the denominator is serious to the extent that it leads Professor Den Hartog to state that greater damping is not necessary for stability in the neighborhood of synchronism. That this is the case, however, follows again from Fig. 5, when it is seen that as $\rho > 1.0$, both $p$ and $r$ must increase to make $p' < 0$. In discussing Fig. 5, Professor Den Hartog has assumed that I had intended to represent the relations between the five variables $\rho, p, r, \omega_s$ and $\delta\tau$ in this diagram. This obviously would be impossible—and, as is stated in the paper, the figure represents the conditions concerning the actual case of parallel operations of generators. Thus, for Fig. 5, $\omega_s$ is kept constant at 20 radians per sec and $\delta\tau$ at $0.03 \times 11 = 0.33$; and $p$ and $r$ are studied in pairs, bringing out the very important conclusions (33), (34), and (35). Professor Den Hartog's extension of this phase of the study to include arbitrary variations of all five variables, in dimensionless form, is a very desirable way of studying all such problems, and is heartily endorsed.

Regarding the development of equations (33), (34), and (35) from (31), the results were obtained as stated, by neglecting $p$ and $r$ with respect to $\omega_s$, except for $\rho = 1.0$.

With reference to Professor Den Hartog's concluding remarks concerning Föppl's work, this latter author considered the case of two generators driven by two prime movers, and mechanically coupled, as shown in Fig. 2 and neglected damping in the generator systems as well. The references to Föppl's other work, and Hort's have to do with the conventional parallel operation problems, that are handled better in the references the author has cited. It is to be appreciated that the role of generator damping represents the fundamental contribution of this paper, as is emphasized in the conclusions.

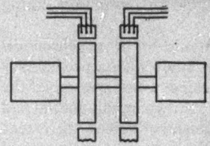

FIG. 2

Mr. Ingram's remarks are well taken, but I believe the first to point out the inherent instability in an improperly designed Watt's governor is due to Maxwell, who showed that a 3rd degree algebraic equation represented the facts.

In answer to Mr. Rogers, the term $K_1 E^{-\frac{R}{L}t}$ has been purposely omitted, since the relation (1.3) in the paper represents the damping and synchronizing effects for continuous oscillation. Concerning the probability of stability involved in the interaction of governor oscillation and the torsional vibration of the elastic system, this practically will never occur, since the latter natural frequency usually is much too high.

Interesting comments were received from Professor Palmer of the University of Colorado, who applied Guillemin's method[3] with a certain amount of desirable conciseness, although losing some of its clarity. The author would also call attention to a vacuum tube circuit analogue of the problem as discussed in "Non-Unilateral Oscillations," *Journal of the Franklin Inst.*, Dec. 1932.

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[1] Föppl, *Elektrotechnische Zeitschrift*, 1902, p. 59, where also the case of dry-friction is treated.

[2] Tolle: l.c. 2nd ed. pp. 600-635, in particular p. 628. Föppl: *Vorlesungen, etc.*, Vol. VI, pp. 293-332: 1st ed. 1910. Hort: *Technische Schwingungslehre*, 2nd ed. 1922, p. 266-273 and pp. 607-615.

[3] A.I.E.E. TRANS., April 1928, p. 361.

# Synchronous-Motor Pulling-Into-Step Phenomena

## Mathematical Solutions of Various Idealized Differential Equations of Motion Made Upon the Differential Analyzer

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***Synopsis.***—*The Differential Analyzer at the Massachusetts Institute of Technology has made possible the rapid and accurate solution of the idealized non-linear differential equations of motion of synchronous motors which describe the pulling-into-step transients. The purpose of this paper is to present the results of these solutions in a useable form. These results give a rather complete analysis of the phenomena, and thus enable the determination of the performance of practically any machine.*

*One of the factors which is considered in this paper is the time constant of the field circuit with the armature short-circuited. Curves are given showing the additional load which may be synchronized when the field switching is angularly controlled to the best angle. The influence of salient poles has been considered as well as non-uniformity of the amortisseur winding. The practical application of the study is indicated by a numerical example.*

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### INTRODUCTION

A MECHANICAL calculating machine[1] named the "differential analyzer" has been developed at the Massachusetts Institute of Technology under the direction of Dr. Vannevar Bush. This machine has made it possible to solve rapidly and accurately the non-linear differential equations which represent the constraints upon the motions of synchronous motors during transient conditions.

Three previous investigations[3,4,5] of synchronous-motor phenomena have been made with a preliminary experimental calculating machine[2] which was called the product integraph. The difficulties of manipulation and the inherent errors of this machine limited the extent and accuracy of the solutions. Now, with the new and accurate differential analyzer, all of the previous work upon the pulling-into-step problem has been repeated and greatly extended. The solutions have been extended to include the "best" switching condition and the condition for "ultimate" synchronization, as well as the "worst" switching condition, which was the goal of the previous investigations. Complete maps of the regions of stability and non-synchronous operation have been determined for all practical cases. Also the effect of the field time constant has been included as another factor.

The purpose of this paper is to present the data from the solutions. Readers are referred to the previously-mentioned articles (4 and 5) for background, the latter containing a rather extensive bibliography of previous work on the problem.

The charts compiled from the results of many solutions make it possible to calculate quantitatively the advantages and benefits of angularly controlled field switching. The benefits are summarized as follows:

1. From 0 to 45 per cent more load can be synchronized with switching controlled to approximately the most favorable angle, compared with that for the case of ultimate synchronization. The gain depends upon the relative damping factor and the relative time constant of the motor as shown in Fig. 7. The largest gain occurs with high-resistance amortisseur windings, large inertia loads, and small field time constants.
2. With angularly controlled field switching, a given motor and load can be pulled into step from a larger slip. The practical meaning of this is that the amortisseur windings do not need to raise the speed to as high a value. Therefore, higher-resistance amortisseur windings may be used, resulting in better starting characteristics.
3. When the field is switched at the most favorable angle the slip during the transient never exceeds its initial steady-state value. For the most unfavorable switching condition the slip during the transient is from 60 to 200 per cent larger than its initial steady-state induction-motor value, depending upon the relative damping factor as shown in Fig. 8.
4. Favorable switching minimizes the mechanical and electrical surges that accompany the pulling-into-step transient when the field of a motor is applied at unfavorable angles.

Thus controlled field switching offers advantages for synchronous-motor applications where the starting conditions are difficult, the inertia is large, or the load at the time of pull-in is large.

### CYLINDRICAL ROTOR OR SYNCHRONOUS INDUCTION-MOTOR CASE

In any round-rotor synchronous induction motor brought up to speed as an induction motor, there are

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1. For references see bibliography.

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six major factors that determine whether the motor will pull into step. These are:

1. The load on the motor during the synchronizing period.
2. The maximum synchronizing torque due to the synchronous-motor effect.
3. The field time constant.
4. The induction torque-slip characteristic. (Assumed linear.)
5. The inertia of the motor and connected load.
6. The switching angle, $\theta_o$, which exists when the exciter is connected, and which is the electrical angle between the axis of the actual field pole and an imaginary field pole that would generate the terminal voltage on open circuit.

When the above six factors are known the data given in this paper makes it possible to determine the maximum shaft load with which the motor will synchronize and the most favorable switching angle $\theta_o$. Since it is desirable to have the motor pull into step on the first swing through the steady-state operating angle, the criterion established for the pulling-into-step is that the final steady-state operating angle shall be attained without the motor swinging more than once through a complete generator cycle after the field is applied.

The equation of the pulling-into-step of a synchronous induction motor is generally accepted to be of the form

$$P_j \frac{d^2\theta}{dt^2} + P_d \frac{d\theta}{dt} + P_m \sin\theta\,(1 - \epsilon^{-\alpha t})\,\mathbf{1} = P_L \qquad (1)$$

The significance of the various terms is given below:

$P_j$ = coefficient which when multiplied by the acceleration in electrical degrees per second per second, gives the component of power accelerating the inertia (at synchronous speed).

$P_d$ = coefficient which when multiplied by the slip in electrical degrees per second, gives the component of power due to the induction-motor effect. (Assumed constant in the solutions.)

$P_m$ = maximum power due to the synchronizing action of the field current.

$P_L$ = amount of shaft load at synchronous speed (considered constant in the solutions).

$\frac{d^2\theta}{dt^2}$ = acceleration in electrical degrees per second per second.

$\frac{d\theta}{dt}$ = slip in electrical degrees per second.

$\theta$ = the angle in electrical degrees which exists between the axis of the actual field pole and an imaginary field pole that would generate the terminal voltage on open circuit.

$\theta_o$ = the value of $\theta$ that exists when the exciter is connected.

$(1-\epsilon^{-\alpha t})$ = term taking into account the effect of the field time constant.

$\mathbf{1}$ = Heaviside's unit function which is zero before and unity after time equals zero.

In deriving the equation it is assumed that the armature currents and potentials are sinusoidal, that the applied armature and field potentials are constant, and that the stator resistance and the effect of the rotor leakage inductance are negligibly small.

To facilitate solution by the differential analyzer the equation can be reduced to a more convenient form by dividing through by $P_m$ and replacing $t$ by a new dimensionless variable $\lambda$; this gives the equation as

$$\frac{d^2\theta}{d\lambda^2} + k\frac{d\theta}{d\lambda} + \sin\theta\,(1 - \epsilon^{-a\alpha\lambda})\,\mathbf{1} = \frac{P_L}{P_M} \qquad (2)$$

where

$$k = \frac{P_d}{\sqrt{P_j P_m}} \text{ and } \lambda = \frac{t}{a}$$

In the reduction of equation (1) to the above form, $a$ is selected so that the coefficient of the acceleration term and the coefficient of the sine term shall be unity. For this condition

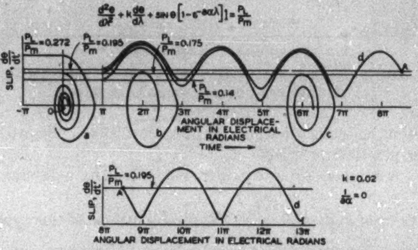


Fig. 1—Actual Differential Analyzer Slip-Angle Solutions of the Equation of Motion of a Round-Rotor Synchronous Motor During Pulling-Into-Step Transients

$$a = \sqrt{\frac{P_j}{P_m}}$$

The factor $k$ is called the relative damping coefficient and combines the terms $P_d$, $P_j$, and $P_m$, which depend upon the motor under consideration, into one factor. Thus all machines having any given value of $k$ respond with similar electromagnetic transients, in terms of $\lambda$, when similar disturbances are imposed upon them, regardless of the size of the machine.

The relative damping coefficient $k$ is a numeric which contains the dimensions of angle and is proportional to the square root of the magnitude of the unit used for measuring angle. In the solutions that follow, angle is measured in electrical degrees. If electrical radians are used, $k$ would be multiplied by the factor $\sqrt{\frac{180}{\pi}}$.

The factors influencing the pulling-into-step of the motor have now been reduced to four.

1. $k$ = the relative damping coefficient.
2. $P_L/P_m$ = the load ratio.
3. $\theta_o$ = the value of $\theta$ when the exciter is connected.
4. $\dfrac{1}{\alpha a}$ = relative time constant.

To be able to predict what will happen in any particular machine it is necessary to have a range of solutions covering all values of these coefficients met with in practical machines.

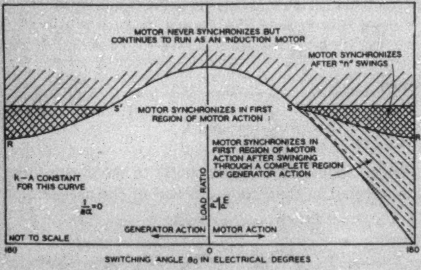

MOTOR NEVER SYNCHRONIZES BUT CONTINUES TO RUN AS AN INDUCTION MOTOR
MOTOR SYNCHRONIZES AFTER "n" SWINGS
S'
S
MOTOR SYNCHRONIZES IN FIRST REGION OF MOTOR ACTION
R
R
MOTOR SYNCHRONIZES IN FIRST REGION OF MOTOR ACTION AFTER SWINGING THROUGH A COMPLETE REGION OF GENERATOR ACTION
k—A CONSTANT FOR THIS CURVE
1/αa=0
LOAD RATIO
PL/Pm
GENERATOR ACTION
MOTOR ACTION
NOT TO SCALE
180
0
180
SWITCHING ANGLE θ0 IN ELECTRICAL DEGREES

FIG. 2—DIAGRAMMATIC CHART CLASSIFYING THE SWITCHING ANGLES AND CORRESPONDING LOAD RATIOS

A number of solutions were made, each for a different value of $k$, $\theta_o$, and $\dfrac{1}{\alpha a}$. Typical solutions of this type are shown in Fig. 1, curves of slip against angle for $k = 0.02$ and $\dfrac{1}{\alpha a} = 0$.

For the chosen value of $k$, initial switching angle and load ratio, the curves show how the angle $\theta$, and the slip, subsequently varied. Curves $b$, $c$, and $d$, $f$, Fig. 1, are for $k = 0.02$ and $\theta_o = 180$ deg. For a value of $\dfrac{P_L}{P_m} = 0.14$ (curve $b$) the machine synchronized on the first swing, conforming with the criterion. For a value of $\dfrac{P_L}{P_m} = 0.175$ (curve $c$) the machine synchronized on the third swing, hence did not conform to the criterion. From a family of curves such as these the plot in Fig. 2 was constructed.

After making several solutions of the type in Fig. 1 it became apparent that a critical solution is one that gives a final steady-state operating position on the unstable portion of the power-angle curve, such that the synchronous torque then developed is the same as it would be if the machine were operating in a stable position. In other words, the motor reaches a condition of zero slip and zero acceleration in the unstable region of the power-angle curve, with the load torque exactly balanced by the synchronous torque. When the relative field time constant is zero, this knowledge permits the use of a valuable characteristic of the differential analyzer, namely, that it can be operated either forward or backward. If the final conditions for a critical solution are known, the machine may be set to conform to these conditions and operated so that time proceeds in a reverse direction. It will then solve for the initial conditions necessary to give the known final result.

In Fig. 2 the various possible types of solutions and the switching conditions which give rise to them are classified into regions on a chart. A point on this chart has as its co-ordinates the load ratio $\dfrac{P_L}{P_m}$ and the switching angle $\theta_o$, the entire chart being for a particular value of $k$ and of $\dfrac{1}{\alpha a}$. Points that lie in the unshaded portion of the plot show the load ratios and switching angles for which the motor will synchronize without swinging beyond the first region of motor action. For points lying in the region shown by dotted cross-hatching the motor will synchronize in the next region of motor action after passing through a complete region of generator action. Points within these two regions are the only ones for which the motor will synchronize and satisfy the criterion. For points lying in the region shown by lattice cross-hatching the motor will eventually synchronize after passing through a number of motor and generator cycles. It was definitely proved that points lying within these three regions are the only ones having co-ordinates of load ratio and switching angle for which a motor with the given value of $k$ and $\dfrac{1}{\alpha a}$ will ever synchronize. In other words, for points

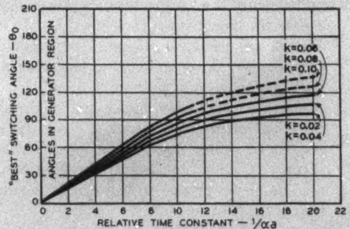


FIG. 3—CURVES FOR ROUND-ROTOR SYNCHRONOUS MOTOR

Showing positions of best switching angles as functions of the relative time constant for constant values of $k$. Note that all the angles refer to generator region in the region shown by plain cross-hatching the motor will never synchronize but will continue to run as an induction motor.

The load ratio corresponding to points $S$ and $S'$ becomes significant since it is the maximum that can be eventually synchronized when the switching angle is uncontrolled. This load ratio may be called *the ultimate load ratio.*

With the data obtained from families of curves of the type in Figs. 1 and 2, Figs. 3 to 7 were prepared. The captions are self-explanatory, hence it is not necessary to discuss the curves here.

## SALIENT-POLE SYNCHRONOUS MOTOR

The theory of the pulling-into-step phenomena for a salient-pole synchronous motor has been given in the results of a previous study[5] made on the product integraph. Some of this work has been repeated and extended with the new differential analyzer.

The salient-pole-motor case involves the use of a more comprehensive equation, as described in the reference mentioned above. Only the graphical results of the present study are given in this paper. The methods of obtaining the results are identical with those used for the round-rotor case with the exception that the initial slip is not constant. The variation of the initial slip is due to the torques caused by the reluctance effect of the salient poles and the incompleteness of the amortisseur windings. Both of these torques are functions of angular displacement.

Fig. 9 gives two curves (marked $P_R/P_m = 0.3$) showing the range of load ratio which will just allow pulling-into-step as a function of the relative damping coefficient for a salient-pole machine having a reluctance torque equal to 30 per cent of that torque which is a sine function of the angular displacement. In these curves the damping is considered to be equivalent to that of a round-rotor motor; that is, the induction-motor torque does not vary with the angular displacement. The lag of the building up of the field has been neglected for this aspect of the problem, since the conclusions of the extensive study of the effect of the field transient on the round-motor machine undoubtedly apply to the salient-pole machine.

Other curves (marked $b = 0$) on Fig. 9 show the largest load ratios which are permissible as a function of the relative damping factor for a cylindrical rotor motor with a damping torque that varies as a cosine squared function of the angle. The effect of the field time constant was also neglected in these curves for the same reason as in the salient-pole case.

The curves of Fig. 9 show that the salient poles and incomplete amortisseur windings do not greatly influence the ratio between the critical load ratio and the relative damping coefficient. The explanations for this are:

1. The excursion of the angle covers such a large range of values that only the average coefficients of the differential equation are of importance.

2. The torque variations before the field circuit is energized cause the instantaneous initial slip to vary in such a manner that the initial slip is a maximum at what would otherwise be the most favorable switching angle. Thus the expected gain from saliency is largely neutralized.

The maximum slip during the transient is plotted as a function of the relative damping factor in Fig. 8. The salient-pole motor has a larger variation of the maximum slip than does the round-rotor machine.

## PRACTICAL APPLICATION OF THE DIFFERENTIAL ANALYZER SOLUTIONS

The previously-mentioned papers[4,5] demonstrated the manner in which the solutions were applied to determine whether or not a synchronous motor would synchronize for the *worst switching condition.* A mathematical inequality was determined from the slope of the curve that separated the region of unstable solutions from the stable ones, and thus made it possible to obtain useful relationships such as expression 5 of reference 5, or expression 7 or 8 of reference 4. The data from the differential analyzer solutions which were made for this paper show the error that is made by taking such a linear relationship. Fig. 9 shows the actual curve for the most unfavorable switching condition. If the load ratio is between the limits 0.1 and 0.8 it is justifiable to use a straight-line relationship which is certainly within the precision of the determination of the coefficients and constants of a synchronous motor.

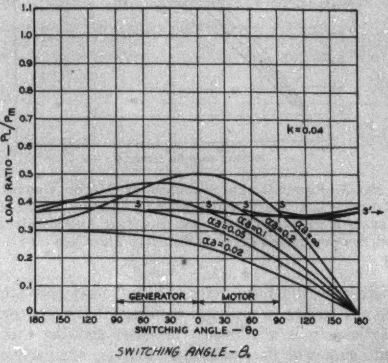


FIG. 4—CURVES TAKEN FROM THE RESULTS TO SHOW THE EFFECT OF THE TIME CONSTANT OF THE FIELD CIRCUIT FOR A ROUND-ROTOR SYNCHRONOUS MOTOR

The curves in this paper make it possible to calculate quantitatively the additional load that may be synchronized if the field switch is closed at the *most favorable switching angle.* As may be seen from Fig. 4, this angle may be varied about 10 degrees from the optimum value without seriously influencing the maximum load ratio.

This should permit considerable simplification of the field switching device.

There is an important factor which is always present to some degree in all motors but which has been neglected in this study. This factor is the amount of non-linearity of the slip-torque curve of the motor. The results given apply only to motors which have linear slip-torque curves for the entire transient excursion of slip and which have the same slip-torque curve before as well as after the field circuit is energized. Therefore engineering judgment needs to be exercised when applying the results to practical motors. If the slip-torque relationship is non-linear, the chart showing the per cent gain will be pessimistic, that is, angularly-controlled field switching will yield a larger gain than is predicted by the results of this study. The reason for this is due to the different range of the values of slip encountered for the best switching condition and for the ultimate or the worst case. As can be seen from the characteristic solutions shown in the left-hand side in Fig. 1, the slip for the best switching condition never exceeds its initial value, while the slip for the worst case increases greatly because of the swing through the generator region. Since the deviation from the linear part of the slip-torque curve increases as the slip increases, the results given for switching under the most unfavorable angle will be affected more than the results for switching at the most favorable angle. Thus motors having values of $k$ and $\frac{1}{\alpha a}$, for which the charts show no gain, may actually realize a gain because of the non-linear aspects of the slip-torque curve.

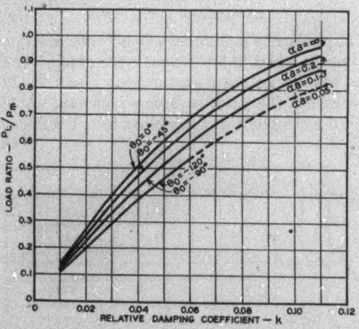


FIG. 5—ROUND-ROTOR SYNCHRONOUS MOTOR CURVES OF MAXIMUM LOAD RATIO WHICH MAY BE PULLED-INTO-STEP, *vs.* RELATIVE DAMPING COEFFICIENT FOR BEST ANGLE SWITCHING AND FOR CONSTANT VALUES OF RELATIVE TIME CONSTANT

In what follows, the data that are necessary for determining the synchronizing characteristics of a synchronous motor are listed, and a complete sample calculation is given. The units used for numerical values on the curves correspond to electrical degrees and therefore the angle must be expressed in electrical degrees. A convenient unit for torque is the synchronous kilowatt since the speed does not vary far from synchronous, and since the machine characteristics usually are expressed in kilowatt units.

*Necessary Data*

$P_j$ inertia coefficient in kilowatts per electrical degree per second per second.

$$P_j = 18.6\,\frac{(WR)^2 f}{p^2} \times 10^{-6}\ \text{kw/elec deg/sec}^2 \qquad (3)$$

where $(WR)^2$ is the moment of inertia in pound-feet.[2]

$f$ is the frequency.

$p$ is the number of poles.

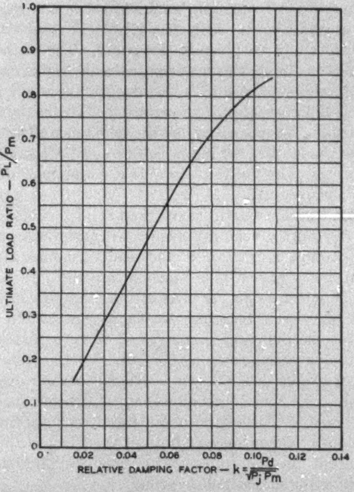


FIG. 6—ROUND-ROTOR SYNCHRONOUS MOTOR "ULTIMATE" LOAD RATIO CURVE FOR ANY VALUE OF SWITCHING ANGLE $\theta_0$, AND ANY FIELD TIME CONSTANT

$P_d$ damping coefficient in kilowatts per electrical degree per second.

$$P_d = \frac{P_L}{360\, fs}\ \text{kw/elec deg/sec}^2 \qquad (4)$$

where $P_L$ and $s$ are taken from the near-synchronous straight-line portion of the slip-torque curve.

$P_L$ = load torque in synchronous kilowatts.

$s$ = the corresponding per-unit slip.

$P_m$ synchronizing torque in kilowatts for $\theta = 90$ degrees.

$P_L$ load on the motor in kilowatts.

$n$ synchronous speed in rpm.

$\frac{1}{\alpha}$ field time constant with armature short circuited.

*Example—Sintering Fan Drive*

8-pole, 60 kva, 900 rpm, 440-v, 75 hp, 1.0 power factor total $WR^2 = 4{,}000$ pound-feet$^2$

$P_j = 0.0697$ kw/elec. deg/sec.$^2$

$P_d = 0.170$ kw/elec. deg/sec.

$P_m = 117$ kw.

$1/\alpha = T_e = 0.0955$.

$P_L/P_m = 0.477$.

From the above data the following constants may be calculated.

$$k \quad = \text{relative damping coefficient} = \frac{P_d}{\sqrt{P_j P_m}} = 0.0594.$$

$$a \quad = \text{conversion factor} = \sqrt{\frac{P_j}{P_m}} = 0.0244.$$

$$\frac{1}{a\alpha} = \text{relative time constant} = 3.91.$$

The ultimate condition of just synchronizing is read from Fig. 6 entering with $k = 0.0594$ and reading $P_L/P_m = 0.560$. This shows that the motor is conservatively rated provided the slip-torque relationship is approximately linear. If in practise the load should be larger than normal, the curve of Fig. 7 shows that if the angle is controlled to the most favorable switching angle, then about 0.2 per-unit more load than the ultimate can satisfactorily be pulled into step. The most favorable switching angle is 36 degrees (generator) as read from Fig. 3.

### THE DIFFERENTIAL ANALYZER CONNECTIONS

To illustrate the method of solution of this problem using the differential analyzer, a typical case of the round-rotor motor will be considered and the effect of the field time constant taken into account. In order to follow the process more readily, the differential equation of motion will be written in the form:

$$\theta = \int \left[ \int \frac{P_L}{P_m} d\lambda - \int k \, d\theta - \int \sin\theta \, (1 - e^{-\alpha a \lambda}) \, 1 \, d\lambda \right] d\lambda \qquad (5)$$

The differential analyzer performs the operations indicated on the right-hand side of the equation, and the motions of its parts are at all times constrained in accordance with the dictates of the equation. At any instant during a solution the position of any particular shaft represents the instantaneous value of the term or group of terms of the equation which the shaft represents. Any two of these shafts may be coupled at will to the abscissa and ordinate shafts of a curve—drawing mechanism or output table. As the solution proceeds, the curve traced out shows the functional relationship between the quantities which the respective shafts represent, and therefore constitutes a solution to the differential equation.

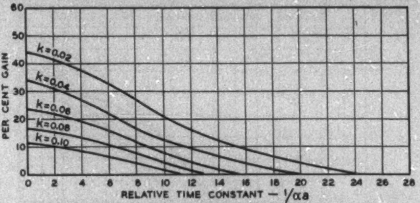


FIG. 7—ROUND-ROTOR SYNCHRONOUS MOTOR CURVES

**Showing the additional load which may be pulled-into-step when field switching occurs at the "best" angle (as a ratio to that which may be "ultimately" pulled-into-step) as a function of the relative time constant**

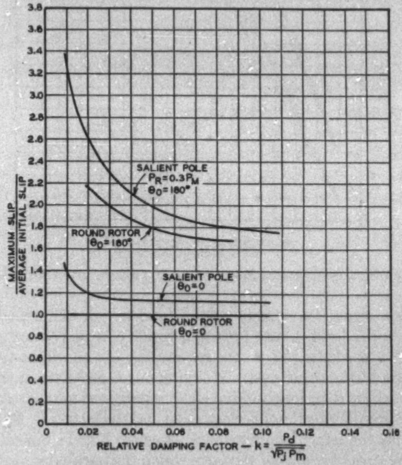


FIG. 8—PLOT OF THE TRANSIENT SLIP VARIATIONS

As will be seen from Fig. 10, the machine consists of integrators, input tables, and output tables, which may be connected together by means of longitudinal or cross shafts. For this particular problem the inter-connections are shown schematically in Fig. 11.

Referring to the integrators, $I_1$, $I_2$,—$I_5$, shown on Fig. 11, each may be considered as a unit with three shafts, the angular motions of which are $u$, $v$, and $w$, so connected that at all instants $u = c \int w\,dv$. An input table $T_1$, $T_2$, has two shafts, $X$ and $Y$, one of which moves a pointer horizontally in the direction of abscissas, and the other vertically in the direction of ordinates across a plot of a function. One shaft is controlled manually to keep the pointer on the plot, thus giving at all times $Y = f(X)$. In order that the sum of two terms may be handled, "adders" or differential gears $A_1$ and $A_2$ are provided which can be connected to three shafts so that the revolutions of one will be the sum of the other two. In laying out a problem on the machine each longitudinal shaft is assigned to one term or group of terms of the equation and the letters $A$, $B$,—$L$ at the left of the schematic diagram Fig. 11 indicate the turns per unit of the term which the particular shaft represents. For a detailed description of the other important parts of the machine, such as torque amplifiers which make the integrators possible, and the front-lash units, etc., the reader is referred to reference (1) in the bibliography.

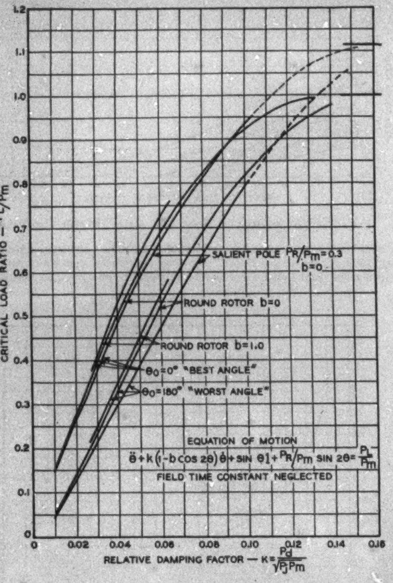


FIG. 9—SYNCHRONOUS-MOTOR CRITICAL-LOAD-RATIO CURVES

Neglecting scales and directions of rotation for the present, we shall proceed with the particular set-up. On table $T_1$ is placed a plot of $1 - e^{-\alpha a\lambda}$ as ordinate and $\lambda$ as abscissa, and on table $T_2$ is plotted $\sin\theta$ as ordinate and $\theta$ as abscissa. According to equation (5) the angle $\theta$ is the integral with respect to $\lambda$ of the sum of three integral expressions. The three integrals are the load ratio $\frac{P_L}{P_m}$ and the product $\sin\theta\,(1 - e^{-\alpha a\lambda})$ integrated with respect to $\lambda$, and the relative damping coefficient $k$ integrated with respect to $\theta$. To perform the process of integration the procedure is as follows:

The shaft $v$ of integrator $I_1$ is connected to the longitudinal shaft $L$ representing $\lambda$ and the shaft $w$ is displaced proportional to $\frac{P_L}{P_m}$. Connecting $u_1$ to the shaft $G$ then gives the motion of $G$ proportional to $\int \frac{P_L}{P_m}\,d\lambda$. The integrator $I_2$ has its shaft $w_2$ displaced proportional to $k$ and its shaft $v_2$ connected to shaft $A$ representing the units of $\theta$. The motion of the shaft $u_2$ then represents $\int k\,d\theta$ and is connected to shaft $D$. The integral of the product of the sine term and the exponential is readily handled by means of two integrator units, one unit being used to integrate, the other to multiply. The abscissa shaft $X_1$ of table $T_1$ is connected to shaft $L$ which results in the pointer on the curve of table $T_1$ being displaced horizontally according to $\lambda$. The ordinate shaft $Y_1$ is then given a motion proportional to $(1 - e^{-\alpha a\lambda})$ by keeping the pointer on the plot. The shaft $Y_1$ connects to shaft $J$ which in turn connects to shaft $w_3$ of the integrator $I_3$. The integrator has its shaft $v_3$ connected to shaft $L$ and so gives the motion of the shaft $u_3$ proportional to the $\int (1 - e^{-\alpha a\lambda})d\lambda$. To perform the multiplication the shaft $u_3$ is linked with the $v_4$ shaft of integrator $I_4$ through the shaft $H$. The shaft $w_4$ is displaced proportional to $\sin\theta$ by being connected to the shaft $B$ which in turn is controlled as to motion by the shaft $Y_2$ of table $T_2$. The shaft $Y_2$ is turned by hand to keep the pointer on the plot. The

FIG. 10—ILLUSTRATION OF THE DIFFERENTIAL ANALYZER AT THE MASS. INSTITUTE OF TECHNOLOGY FOR SOLVING NON-LINEAR DIFFERENTIAL EQUATIONS

motion of shaft $u_4$ of integrator $I_4$ then becomes proportional to $\int \sin\theta\,[1 - e^{-a\alpha\lambda}]\,d\lambda$ and is connected to shaft $F$. The motions of the shafts $G$ and $F$ are then added by the adder $A_1$ and its output $G$ and $F$, connected to $E$. Adding the motions of the shafts $E$ and $D$ by the adder $A_2$ and connecting the output to shaft $C$ gives the motion of shaft $C$ proportional to the value of the expression

$$\int \frac{P_L}{P_m}\,d\lambda + \int k\,d\theta + \int \sin\theta\,(1 - e^{-a\alpha\lambda})\,1\,d\lambda. \quad (6)$$

The angle $\theta$ is the integral of all this with respect to $\lambda$, hence shaft $C$ is connected to shaft $w_5$ of integrator $I_5$ and the shaft $L$ connected to the shaft $v_5$. The motion of the shaft $u_5$ then becomes

$$\int\Big[\int \frac{P_L}{P_m}\,d\lambda + \int k\,d\theta + \int \sin\theta\,(1 - e^{-a\alpha\lambda})\,1\,d\lambda\Big]\,d\lambda \quad (7)$$

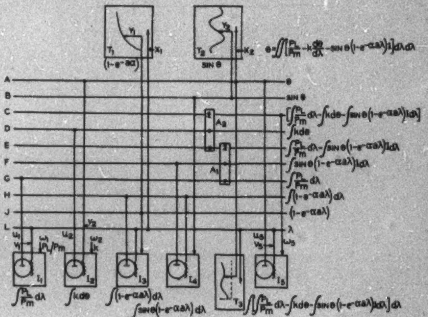
and equals the angle $\theta$. Connecting $u_5$ to shaft $A$ and $A$ to the abscissa $X_2$ of table $T_2$ now closes the set-up and the machine is constrained in accordance with the requirements of the equation. It is only necessary to set the units for the initial conditions, such as the value of $k$, $\frac{P_L}{P_m}$, and switching angle $\theta$, before proceeding with a solution. Rotating the time shaft sets all the shafts in motion and, provided the pointers are kept on the plots on tables $T_1$ and $T_2$, a solution will be obtained in the form of a curve by connecting the required shafts to the answer table $T_3$. As connected in Fig. 11, the curve is a plot of angle against time during the period of synchronization.

The scales and directions of rotation are readily handled by inserting gear trains at the various coupling points of the machine.

It is probably worth while mentioning that, for the major part of the work, it is unnecessary to cause the machine to trace out a curve for the solution. As the investigation was mainly concerned with the question of whether the machine would synchronize on the first swing, the operator controlling the ordinate shaft on table $T_2$ could always tell by watching the motion of the pointer whether the machine would synchronize or not. For a critical solution the motor reaches synchronous speed with zero acceleration and with the angle between the rotor and stator fields just sufficient to develop the load torque, with the machine operating in the unstable region of the power-angle curve. If the operator observes the angle increase beyond the critical angle he knows that the motor will not synchronize on that swing. If he observes the angle reach a maximum value and then commence to decrease, he knows that the machine will synchronize after a few oscillations about the ultimate steady-state angle in the stable region of the power-angle curve, and the solution need not be continued beyond that point. By this means the time required for a solution having a given set of initial conditions was about three to five minutes.

### ACKNOWLEDGMENT

The authors wish to acknowledge the kind assistance and the many helpful suggestions given by the members of the staff at the Massachusetts Institute of Technology, and especially to Doctor V. Bush, Professor G. C. Dahl, Professor W. V. Lyon, Professor H. L. Hazen, Mr. Chas. Kingsley, Jr., and to Mr. S. H. Caldwell. The suggestions and interest of Mr. P. L. Alger, Mr. Ira Terry, and others of the General Electric Company are appreciated.


$T_1$
$Y_1$
$X_1$
$(1-e^{-a\alpha})$
$T_2$
$Y_2$
$X_2$
SIN θ
$\theta = \iint\big[\frac{P_L}{P_m} - k\frac{d\theta}{d\lambda} - \sin\theta(1-e^{-\alpha a\lambda})1\big]d\lambda\,d\lambda$
A
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$\int\frac{P_L}{P_m}d\lambda - \int\sin\theta(1-e^{-\alpha a\lambda})1\,d\lambda$
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$\int\frac{P_L}{P_m}d\lambda$
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$\int(1-e^{-\alpha a\lambda})\,d\lambda$
$\int\sin\theta(1-e^{-\alpha a\lambda})\,d\lambda$
$\int\big[\int\frac{P_L}{P_m}d\lambda - \int k\,d\theta - \int\sin\theta(1-e^{-\alpha a\lambda})1\,d\lambda\big]\,d\lambda$

FIG. 11—SCHEMATIC DIAGRAM OF DIFFERENTIAL ANALYZER

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## Discussion

**I. A. Terry:** This paper presents a further step in the analysis of the phenomena associated with the pulling-into-step of a synchronous machine. Two years ago, Messrs. Edgerton and Fourmarier gave the results of integraph solutions of the same problem based upon simplifying assumptions.[1] One of the ~~most~~ important of these assumptions as affects the performance was that the field time constant was zero. This implied the immediate presence of full flux in the air gap at the instant the field switch was closed. The previous paper developed a criterion for the slip from which a synchronous motor always could pull into step. Test data presented in a discussion by Mr. D. W. McLenegan and the writer[2] showed that this relation between slip and the various machine quantities gave such a value that the machine always could pull into step. The data suggested some pessimism in the formula for the pulling-into-step characteristics indicating that under certain conditions other factors not considered in the analysis acted beneficially. Recognizing the fact that the assumptions of the previous paper may not represent the facts, Mr. Edgerton and his associates have obtained an analysis of great merit and one which will be of considerable value to the electrical industry as a whole. The practical value of such solutions is evident when one considers the great variety of synchronous motor drives that are required to pull into step under load.

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[1] Bibliography 5.

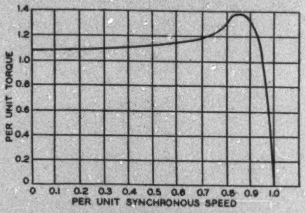

Fig. 1—Torque-Speed Curve of 225-Hp, 450-Rpm, 1.0-Power Factor Synchronous Motor

One of the important features of the present paper is showing the benefits that should be obtainable by properly timing the application of field current to the synchronous motor. Fig. 7 of the paper indicates the per cent gain that may be obtained by such timing as a function of machine quantities. Test data available on two synchronous motors indicate that considerably more benefit is derived from proper timing for large values of the relative time constant $\frac{1}{\alpha a}$ as is suggested by the authors.

One motor is rated 225 hp unity power factor, 450 rpm, 60 cycles and drives a pump. The motor and connected equipment have a total $WR^2$ of 4,350 lb-ft$^2$. The steady pull out torque is 160 per cent of normal. The short-circuit time constant with the armature short-circuited approximately is 0.25 second. The torque-speed curve is shown in Fig. 1 and the machine is required to pull into step against such a load that at full speed it will be normal. Using the nomenclature of the paper $k = 0.082$ and $\frac{1}{\alpha a} = 30.9$. In making these calculations, $P_d$ was based upon 115 per cent torque at 95 per cent speed. Fig. 7 of the paper indicates practically no gain should be expected from timing the application of field current. Test data indicated that the machine could pull into step approximately 15 per cent greater load by properly timing the application of field.

The other motor is rated 125 hp unity power factor, 514 rpm, 60 cycles and also drives a pump. This machine and its connected apparatus have a $WR^2$ of 1,790 lb-ft$^2$. The steady-state pull out torque is approximately 150 per cent of normal. The short-circuit time constant of the field winding is approximately 0.2 second. The speed torque curve is shown in Fig. 2 and the motor is required to pull into step with a load similar to that of the first machine. For this motor, $k = 0.093$ $\frac{1}{\alpha a} = 24.2$. From Fig. 7 of the paper one would expect to obtain practically no increase in pulling-into-step characteristics by timing the field application. Test data indicated the motor always could pull approximately 20 per cent greater load into step by properly timing the application of field than could always be synchronized with random field application.

It is believed that the principal source of difference between calculated and test results is the assumption made by the authors that the torque slip curve is a straight line throughout the range of slip during the synchronizing. Actually, this is not a straight line as is evident from Figs. 1 and 2. The authors have stated that due to an unfavorable switching condition, the slip during the transient may be from 60 to 200 per cent greater than the initial steady-state induction-motor value. Since these values are based upon straight line characteristics, the effect of a drooping characteristic such that twice slip does not represent twice torque appears to increase the slip during the transient to 300 per cent or even 400 per cent greater than the initial value under extremely unfavorable conditions. Therefore in subsequent swings the machine must accelerate from a much greater value of slip and so the amount of load that may be pulled into step under most favorable conditions may in practise appreciably exceed the value calculated on the basis of a straight torque-speed characteristic.

The comments of the authors on the above reasoning would greatly be appreciated.

**H. E. Edgerton, G. S. Brown, K. Germeshausen, and R. Hamilton:** Mr. Terry's discussion is valuable because it brings out some of the difficulties that are encountered when the results of the paper are applied to practical problems. At the outset of this investigation it was necessary for us to decide upon the number of variables and factors which influenced the pulling into step of synchronous motors. Then we had to eliminate some of them so that a reasonable number of solutions would cover all possible combinations of the remaining factors. For instance, we assumed that the slip-torque curve of the induction-motor effect was a linear relationship simply because of the added ramifications if an attempt is made to introduce the true characteristic. Mr. Terry's curves indicate that this characteristic differs considerably among different machines and as he shows, accounts for a considerable portion of the discrepancy between test and theory.

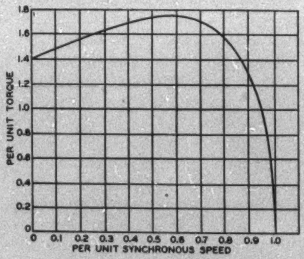

Fig. 2—Torque-Speed Curve of 125-Hp, 514-Rpm, 1.0-Power Factor Synchronous Motor

It is important to point out, however, that a valuable calculation is possible even with practical slip-torque characteristics as in the motors given by Mr. Terry. This calculation gives the maximum amount of load that may be pulled into step for favorable switching conditions. The slip for this case never has an opportunity to exceed appreciably its initial value which is either on or close to the linear part of the slip-torque curve. When making this calculation it is advisable to determine $P_d$ from the slope of a line drawn through the origin of the slip-torque curve and the point corresponding to the initial slip. The results obtained from Fig. 5 then will be conservative, since any non-linearity to the slip-torque curve gives an excess of torque tending to pull the motor into step. From similar reasoning the results obtained from Fig. 7 also will be conservative because for unfavorable switching angles there is considerably less torque available whenever the slip exceeds its initial slip by such large values as it does when swinging through the region of generator action.

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[2] A.I.E.E. Trans., June 1931, p. 778.

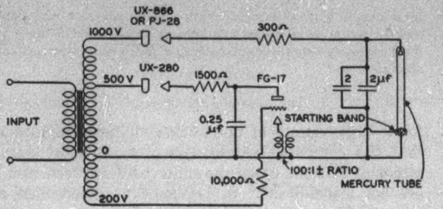

Fig. 3

No difficulties are encountered when using the differential analyzer to solve the pulling-into-step problem taking the actual slip-torque relationship into account. A general solution for all sizes of machines seems quite out of the question however because of the large number of variables.

A factor that has not been stressed sufficiently perhaps is that allowance should be made for any variation in the slip-torque characteristic due to changes in the rotor circuits when the field switch is closed.

The motion pictures of the pulling-into-step phenomena that were shown at the winter convention were taken with stroboscopic light from a mercury arc tube. A disk, rigidly attached to the shaft of the synchronous motor, had an engraved scale around its outer rim. Stroboscopic light produced from the circuit[3] of Fig. 3 was used to illuminate the disk. This light flashes for a few microseconds each cycle in phase with the terminal voltage and when shone upon the disk permits the observation of the power angle, $\theta$. About 200 watts input to the stroboscope circuit are sufficient to produce adequate illumination to take moving pictures such as were shown. The camera was driven by a small synchronous motor exactly at 30 frames per second and the shutter was synchronized so that a picture was taken every other cycle.

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[3] The operation of the stroboscope circuit is explained in the *Review of Scientific Instruments*, October 1932, p. 535.

# Two-Reaction Theory of Synchronous Machines—II

BY R. H. PARK*
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***Synopsis.**—The analysis presented in a previous paper is extended to include a consideration of synchronizing and damping torque during continuous and transient oscillations, the description of an equivalent circuit which has been found useful in calculating the decrement of the short circuit current of interconnected machines, and the derivation of simple approximate formulas for the roots of the equation determining the wave shape of the current on three-phase short circuit.*

THIS paper is a continuation of a paper presented in February 1929,[1] and the presentation presupposes a foreknowledge of the material in that paper.

## A. SYNCHRONIZING AND DAMPING TORQUE OF A SYNCHRONOUS MACHINE CONNECTED TO AN INFINITE BUS, FOR SMALL OSCILLATIONS OF FIXED FREQUENCY AND AMPLITUDE

Equation (**64**) of part I, and the equation following it, define an operational function $f(p)$, such that the electrical torque on the rotor, for small oscillations, is given by the expression

$$\Delta T = f(p) \cdot \Delta \delta \tag{1}$$

where

$$f(p) = \frac{\begin{array}{r}[\psi_{d0}+i_{d0}x_q(p)][(e \sin \delta_0+\psi_{d0}p)z_d(p) \\ +\ (e \cos \delta_0 + \psi_{q0}p)\, x_d(p)] \\ \\ [\psi_{q0} + i_{q0}x_d(p)\,]\,[(e \cos \delta_0 + \psi_{q0}p)\, z_q(p) \\ -\ (e \sin \delta_0 + \psi_{d0}p)\, x_q(p)]\end{array}}{D(p)} \tag{2}$$

Let

$s$ = per unit frequency of oscillation
= $(1/f)$ (oscillations per second)

where

$f$ = normal frequency.

Then introducing a system of vectors rotating at $s$ per unit angular velocity, there is $p = js$, and

$$\overline{\Delta T} = f(js)\, \overline{\Delta \delta} \tag{3}$$

But if $T_s$ and $T_d$ are the synchronizing and damping coefficients there is also

$$\overline{\Delta T} = (T_s + T_d p)\, \overline{\Delta\delta} = (T_s + jsT_d)\, \overline{\Delta\delta}$$

from which it follows that

$$\begin{aligned} T_s &= \text{real part of } f(js) \\ sT_d &= \text{imaginary part of } f(js) \end{aligned} \tag{4}$$

This formula for $T_d$ is to be compared with that previously obtained by Nickle and Pierce.[2] C. A. Keener† has computed values of $T_d$ by both formulas for a large variety of operating conditions, and finds that the computed values agree for the most part, although in some cases the differences between them are not insignificant. S. Loukomsky‡ determined a value of $T_d$ experimentally by means of tests on a 15 hp motor. The result obtained in this test was found to differ from the value computed by formula (**4**) by about 16 per cent, which may be regarded as a satisfactory check considering the difficulties involved in the test, and the fact that in the computations no account was taken of any closed rotor circuit other than the field.

## B. DAMPING TORQUE DURING DISTURBANCES

Messrs. Crary and Waring[3] have presented an analysis of the behavior of synchronous machines which shows clearly the nature of the phenomena which take place during disturbances. A method of calculation is also given, based essentially on the numerical evaluation of "Duhamel" integrals. This method of calculation is straightforward and, subject to the fact that armature circuit resistance is neglected, theoretically susceptible of unlimited accuracy. Practically, however, it is believed that it should involve some inaccuracies, and especially if the time constants of quantities under the integral should approach or become less than the time interval used in the step-by-step process.

In view of these considerations the writer believes that ordinarily it will be preferable to employ the usual method of calculation in which field phenomena and synchronizing torque are calculated as though the field were the only circuit on the rotor, and the effect of currents induced in the amortisseur or other "additional" circuits is regarded simply as that of producing a damping torque which may be expressed in the form

$$\text{damping torque} = T_d p\, \delta \tag{5}$$

It can be shown that when this method of calculation is employed $T_d$ should represent the damping torque coefficient for small oscillations about the angle $\delta$ which would obtain if the field winding had no resistance.

Thus when armature resistance is neglected the torque which depends on motion is of the general form given in equation (**49**) of part I, *i.e.*,

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*Calco Chemical Co., Bound Brook, N. J.

[1] For numbered references see Bibliography.

†University of Illinois, Urbana, Ill.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January* 23-27, 1933.

‡General Electric Co., Lynn, Mass.

$$e^2 \sin\delta \frac{x_d - x_d(p)}{x_d x_d(p)} (\cos\delta_0 - \cos\delta)$$

$$+ e^2 \cos\delta \frac{x_q - x_q(p)}{x_q x_q(p)} (\sin\delta - \sin\delta_0) \quad (6)$$

Introduce

$x_d'(p) = x_d(p)$ with infinite amortisseur and field collar resistance.

$x_d''(p) = x_d(p)$ with zero field resistance.

But, as a matter of algebra,

$$\frac{x_d - x_d(p)}{x_d x_d(p)} = \frac{x_d - x_d'(p)}{x_d x_d'(p)} + \frac{x_d'(p) - x_d(p)}{x_d(p) x_d'(p)} \quad (7)$$

Hence it follows that the direct axis component of torque in equation (6) may be resolved into two subcomponents,

$$e^2 \sin\delta \frac{x_d - x_d'(p)}{x_d x_d'(p)} (\cos\delta_0 - \cos\delta)$$

and

$$e^2 \sin\delta \frac{x_d'(p) - x_d(p)}{x_d'(p) x_d(p)} (\cos\delta_0 - \cos\delta) \quad (8)$$

But the first of these components is precisely that which would be computed in the step-by-step method if the amortisseurs and field collars were disregarded.

Also, since the amortisseur time constants are small with respect to the time constant of the field it follows that the difference between the short-circuit current at no-load and the short-circuit current which would obtain if the amortisseur and field collars were of infinite resistance will be very nearly the same whether the field winding has its actual resistance, or whether it has zero resistance, and consequently, that,

$$\frac{1}{x_d(p)} - \frac{1}{x_d'(p)} = \frac{1}{x_d''(p)} - \frac{1}{x_d'} \quad (9)$$

or that

$$\frac{x_d'(p) - x_d(p)}{x_d'(p) x_d(p)} = \frac{x_d' - x_d''(p)}{x_d' x_d''(p)} \quad (10)$$

Consequently it follows that the torque due to motion may be computed by adding to the torque computed by the step-by-step method considering the field alone, a torque equal to

$$e^2 \sin\delta \frac{x_d' - x_d''(p)}{x_d' x_d''(p)} (\cos\delta_0 - \cos\delta)$$

$$+ e^2 \cos\delta \frac{x_q - x_q(p)}{x_q x_q(p)} (\sin\delta - \sin\delta_0) \quad (11)$$

By the superposition (Duhamel's) theorem this torque is equal to,

$$e^2 \sin\delta \frac{x_d' - x_d''}{x_d' x_d''} \Sigma\, a_{dn} \int_0^t \epsilon^{-\alpha_{dn}(t-u)} \sin\delta(u)\, \delta'(u)\, du$$

$$+ e^2 \cos\delta \frac{x_q - x_q''}{x_q x_q''} \Sigma\, a_{qn} \int_0^t \epsilon^{-\alpha_{qn}(t-u)} \cos\delta(u)\, \delta'(u)\, du \quad (12)$$

where the summations are extended over the roots of $x_d''(p) = 0$, and $x_q(p) = 0$.

If $\delta'(t)$ = change in speed is small, in particular if $\delta$ is not changing rapidly relative to the rate of decay of the decrements $\epsilon^{-\alpha_{dn}t}$ and $\epsilon^{-\alpha_{qn}t}$, as is usually the case, the terms $\sin\delta(u)\, \delta'(u)$ and $\cos\delta(u)\, \delta'(u)$ may be taken outside the sign of integration, and consequently the extra torque above that accounted for by the field alone may be expressed as,

$$T_d \delta'(t) = T_d p \delta \quad (13)$$

where,

$$T_d = e^2 \left[ \sin^2\delta \frac{x_d' - x_d''}{x_d' x_d''} \sum \frac{a_{dn}}{\alpha_{dn}} \right.$$

$$\left. + \cos^2\delta \frac{x_q - x_q''}{x_q x_q''} \sum \frac{a_{qn}}{\alpha_{qn}} \right] \quad (14)$$

It will be evident from equation (54) of part I, that this result is substantially equivalent to computing $T_d$ on the basis of zero field resistance, provided that $\delta'(t)$ is small relative to the decrement factors, as has been assumed.

The foregoing analysis has not considered the effects of armature resistance. It is reasonable to suppose, however, that the result arrived at would be found to hold true generally, if a more elaborate analysis including the effects of resistance were carried out.

## C. APPROXIMATE FORMULA FOR THE ROOTS OF THE EQUATION $d(p) = 0$

Formula (32) of part I gives an expression for three-phase short-circuit current in terms of the roots of the cubic

$$d(p) = x_d' x_q T_0 p^3 + [x_d' r T_0 + (x_d + r T_0) x_q] p^2$$

$$+ [r(x_d + x_q + r T_0) + x_d' x_q T_0] p + r^2 + x_d x_q$$

$$= x_d' x_q T_0 (p - \alpha_1)(p - \alpha_a - \alpha_b)(p - \alpha_a + \alpha_b) = 0 \quad (15)$$

It was pointed out in part I that a very good approximation to one of the roots, *i.e.*, the root $\alpha_a$, could be obtained in practical cases by assuming $T_0 = \infty$. This suggests the possibility of determining the roots $\alpha_1$ and $\alpha_b$ in an equally simple manner. We shall find that this can be done as follows:

Assume $T_0$ infinite. This yields

$$p^2 + \frac{x_d' + x_q}{x_d' x_q} r p + \frac{r^2 + x_d' x_q}{x_d' x_q}$$

$$= p^2 - 2\alpha_a p + \alpha_a^2 - \alpha_b^2 \quad (16)$$

Equating like terms yields, first

$$\alpha_a = -\frac{x_d' + x_q}{2\,x_d'x_q}\,r \qquad (17)$$

the result previously found in part I, and second

$$\alpha_b = j\sqrt{\frac{r^2 + x_d'x_q}{x_d'x_q} - \alpha_a^2}$$

$$= j\sqrt{1 - \left(\frac{x_q - x_d'}{2\,x_d'x_q}\,r\right)^2} \qquad (18)$$

If we substitute these values in (**16**), expand, and then equate like terms, three expressions for $\alpha_1$ are obtained. Two of these are found to be unsatisfactory, while the third

$$\alpha_1 = (r^2 + x_dx_q)/(r^2 + x_d'x_q)\,T_0 \qquad (19)$$

is found to coincide with the result previously given by Doherty and Nickle.[4] A detailed check against the exact solution of the cubic shows that equations (**18**) and (**19**) as well as (**17**) may be relied on to give a very close approximation to the true roots of the cubic, in the case of machines of normal design.

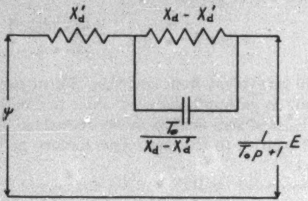

Fig. 1

## D. An Equivalent Circuit for Computing Short-Circuit Current

A simple circuit for computing the no-load short-circuit current in interconnected networks, first used by the writer in 1927, is believed to be worth recording.

The circuit is the same as the usual circuit of the d-c calculating table, in which reactances are represented by resistances, except that the machine reactances are represented by the circuit of Fig. 1.

It may be seen that this circuit fulfills the relations

$$\psi = \frac{1}{T_0p + 1}E - \frac{x_d'T_0p + x_d}{T_0p + 1}\,i \qquad (19)$$

$$= G(p)E - x_d(p)i \qquad (20)$$

and therefore correctly represents the machine at no-load, *i.e.*, when $\psi = \psi_d$, $i = i_d$.

The advantage derived from the use of this circuit is that it not only gives the initial value of the currents, but also their decrements, regardless of the number of interconnected machines. Also it is adapted to the calculation of the effects of quick response excitation. The circuit may also be extended so as to give subtransient as well as transient decrements by shunting part of the resistance $x_d'$ by another capacitor.

While the circuit is principally useful on account of the assistance which it renders in analytical analysis, it may, with the aid of an oscillograph, be used for the prediction of decrements by experimental methods.

A somewhat similar circuit may be employed for computing the decrements of the d-c component. In this circuit the reactances are represented as resistances as in calculating the a-c component, except that the machines are represented merely by simple resistances equal in magnitude to the machine negative phase sequence reactance. Armature circuit resistances, of course, must be included, and are represented by capacitors of magnitude equal to the reciprocal of the resistances which they represent.

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4. Doherty, R. E. and Nickle, C. A., *Three-Phase Short-Circuit Synchronous Machines—V*, A.I.E.E. Trans., Vol. 49, No. 2, April 1930, p. 700.

## Discussion

**S. B. Crary:** The method presented in the paper for the determination of the component of torque due to the motion of the rotor by separating this component into two others, is a definite improvement. This method of approach not only removes the difficulties of computing the component of torque due to the terms having small time constants, as pointed out in the paper, but also allows for the more ready evaluation of changes in the individual circuits as may be affected by design or by changes in the external field circuit.

**Gabriel Kron:** In this and in his other publications Park definitely abandons a method of attack which has been followed by practically all writers on analysis from the first days rotating machines were built and strikes out along a new road with surprising success. He disregards the voltages due to leakage fluxes, common fluxes and introduces only voltages due to *resultant* flux linkages. With their aid he sets up a simple vector equation for the armature

$$\bar{e} = \bar{i}r + p\bar{\psi} + (j\bar{\psi})\,p\theta \qquad (1)$$

(in part I, below Fig. 3[1]) which, divided into its scalar components, (equations (**8**) and (**9**)) forms the foundation for all transient and steady state performance calculations giving in an easy manner rigorous solutions for otherwise difficult problems.

If it is assumed that the field is stationary and the armature is rotating, a simple physical interpretation can be given to equation (**1**) and with this interpretation the equation applies not only for salient-pole synchronous machines but for the rotor of all other asymmetrical machines (induction or commutator machines). Let the current-density wave $\bar{i}$ and the flux-linkage wave $\bar{\psi}$ in the rotor be assumed distributed sinusoidally in space at all instants. Then, due to the instantaneous velocity $p\theta$ of the rotor, a voltage wave $(j\bar{\psi})\, p\theta$ is generated in the rotor by the rotation of the conductors through the resultant flux-density wave $j\bar{\psi}$ located at right angles in space to $\bar{\psi}$. This generated-voltage wave is in space phase with the flux-density wave $j\bar{\psi}$ and is at right angles in space to the induced-voltage wave $p\bar{\psi}$.

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[1] A.I.E.E. Trans., July 1929, p. 718.

With this changed point of view equations (6)—(16) of part I[1] can be interpreted as a transformation of the coordinate axes from the moving terminals to the stationary polar and interpolar space for the purpose of eliminating the troublesome cos $\theta$ term. With this coordinate transformation Park succeeded in making the sudden short-circuit problems of synchronous machines (and thereby of all other rotating machines), with constant speed maintained, identical with those of stationary networks, enabling one to use immediately the expansion theorem without any preliminary operational transformation such as used by Lyon or Ku.

When a sudden speed variation occurs then equations (61) show that an additional transient emf $-(j\psi)\, \Delta p\theta$ appears in the rotor of synchronous machines (and of any other machine) along the resultant flux-density wave that existed before the change. Since the magnitude of the difference of potential across the slip rings is assumed to remain constant the variation of the speed of the slip rings appears as an additional terminal-voltage wave $\Delta\bar{e}$ at right angles in space to $\bar{e}$ (equations (62)) so that the additional transient phenomenon is described as

$$\Delta\bar{e} - (j\bar{\psi})\, \Delta p\theta = \Delta\bar{i}r + p\Delta\bar{\psi} + \Delta\,(j\bar{\psi})\, p\theta \tag{2}$$

showing that the effect of a sudden speed variation (and that of steady hunting) is the same as if no additional speed variation had occurred but two additional emf's had been impressed on the rotor, one along $(j\bar{\psi})$ due to the variation of rotor speed and the other at right angles to $\bar{e}$ due to the variation of slip ring speed. In machines where no slip rings exist $\Delta\bar{e}$ appears only if an actual variation of the terminal voltage occurs. During steady hunting these two emf's are at right angles in *time* since $(j\bar{\psi})\, \Delta p\theta$ is a maximum when the velocity is a maximum and the displacement is zero, while $\Delta\bar{e}$ is a maximum when the displacement is a maximum.

The equations used by Nickle and Pierce (and also by Wagner) are equivalent to

$$\Delta\bar{e} = \Delta\bar{i}r + \Delta\,(j\psi)\, p\theta \tag{3}$$

Doherty and Nickle assumed zero armature resistance and set up equations equivalent to

$$\Delta\bar{e} = \Delta\,(j\bar{\psi})\, p\theta \tag{4}$$

It is interesting that with zero armature resistance the above equation (2), as given by Park reduces also to this same equation (4) since then $p\Delta\bar{\psi}$ cancels $-(j\bar{\psi})\, \Delta p\theta$ (both being at right angles in space from $\Delta e$). Hence the two results are identical and the deviations between the results of equations (2) and (3) are not considerable.

There is one point, however, where Park could have improved his treatment, and that is by abandoning per-unit quantities in analytical work. Just as the concept of leakage flux is indispensable in design work but is a hindrance in analytical work, similarly the per-unit quantities are a handicap in visualizing the phenomena in the field structure by throwing the equations out of symmetry. His field equations could have been written (even with additional field circuits) as

$$\bar{e} = \bar{i}r + p\bar{\psi} \tag{5}$$

which is identical with equation (1) above except $p\theta = 0$. In fact, in this case equations (1) and (5) could have been combined into one vector equation

$$\bar{e} = \bar{i}r + p\bar{\psi} + (j\bar{\psi}_r)\, p\theta \tag{6}$$

where $\bar{\psi}_r$ represents the flux-linkage wave of the rotor and $\bar{\psi}$ that of both stator and rotor.

# Calculation of Single-Phase Series Motor Control Characteristics

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Non-member

and

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***Synopsis.**—This paper describes a simple method of plotting acceleration curves by resolving the reactance and resistance of the transformer, reactive coil, and wiring into a single effective reactance and effective resistance for each open-circuit transformer secondary voltage. By the use of these factors and the motor characteristics simple calculations can be made to determine with any given motor voltage and load the required open-circuit voltage of the transformer. Any errors introduced by the use of the approximate values of effective reactance and resistance are of very minor value and do not appreciably affect the final results.*

THE calculation of the characteristics of a-c equipments as applied to locomotives and cars presents difficulties not found when dealing with d-c equipments, due to the additional variables involved. Characteristics of the motors usually are presented on the basis of constant voltages at the motor terminals, as illustrated in Fig. 1. However, the motors operate in service from an assumed constant-voltage power source with a certain amount of impedance such as transformer, preventive coil, and busbar or cable resistance and reactance in series with the motors. Not only does the vector relation of the impedance drop to the motor voltage vary with motor power factor, but the impedance itself varies depending upon the combination of contactors and transformer taps being used.

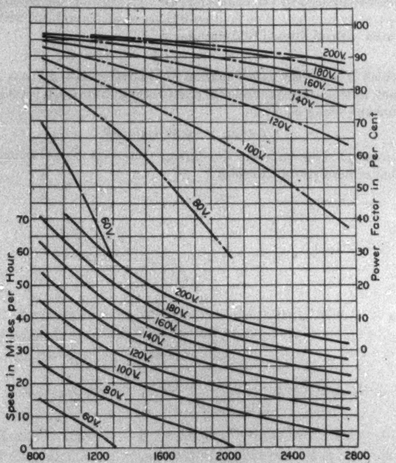

FIG. 1—TYPICAL CHARACTERISTIC CURVES OF SINGLE-PHASE COMMUTATOR TYPE RAILWAY MOTOR

In order to avoid trial and error methods formerly used, wherein the various factors were estimated and then adjusted until all conditions were satisfied, the method described here provides the desired results with a minimum of calculation and curve plotting consistent with accuracy. Certain assumptions are made which, however, are necessary for any method of calculation with which the writers are familiar.

The most important of these assumptions is that regarding transformer impedance. It is assumed that the transformer equivalent reactance and resistance for any tap on the secondary (expressed in ohms) vary as some function of open-circuit secondary voltage $V_t$. The first step in the calculation of the characteristics of the complete equipment therefore is the preparation of such curves of resistance and reactance *vs.* secondary open-circuit voltage, ($V_t$). In the absence of more accurate data the reactance and resistance at rated secondary voltage may be taken as a basis, then assume (*a*) that

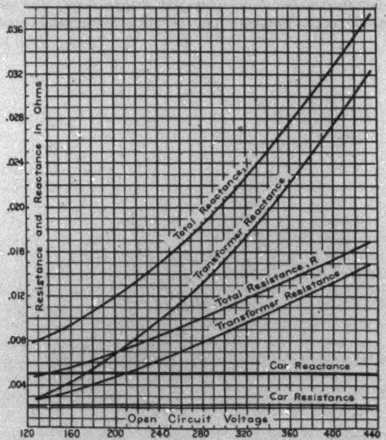

FIG. 2—TYPICAL CURVES OF CIRCUIT AND TRANSFORMER RESISTANCE AND REACTANCE

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

the equivalent reactance in ohms varies as the square of $V_t$, (*b*) that the equivalent ohmic resistance of the primary and secondary are equal at rated voltage, (*c*) that the equivalent resistance of the primary varies as the square of $V_t$, and (*d*) that the resistance of the secondary is directly proportional to $V_t$. It is recognized that due to the manner of connecting the secondary taps the reactance and resistance will vary slightly from the simple relation assumed above. However, the existence of an infinite number of taps having uniformly varying characteristics is an essential premise.

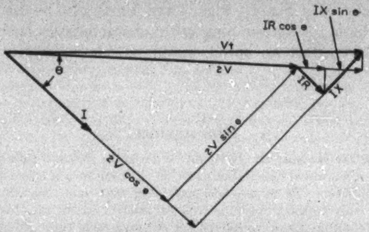

Fig. 3—Vector Diagram Illustrating Exact and Approximate Calculation of $V_t$

For convenience in calculating, it is advisable to combine all other reactances and resistances, such as that of the preventive coils, busbars, etc., with that of the transformer, giving curves of total reactance, $X$, and total resistance, $R$, as in Fig. 2.

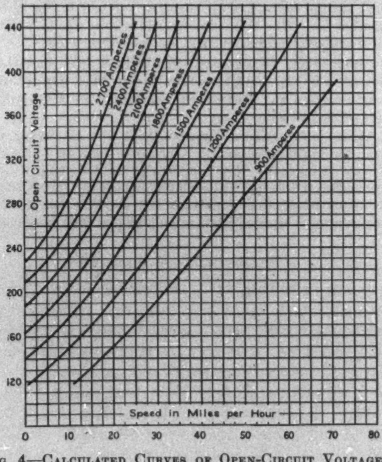

Fig. 4—Calculated Curves of Open-Circuit Voltage *vs.* Speed for Constant Currents

The reactance and resistance of the preventive coil can be considered for the purposes of this calculation to be constant since the load currents through the two legs of the coil are balanced. The reactance and resistance of the car or locomotive wiring can also be treated as having a constant value as the variations due to change of connections are insignificant in comparison with the other factors in the calculations. These values for wiring may be determined from tests or estimated from knowledge of the characteristics of previous installations.

When multiple circuits are involved, it is, of course, necessary that all factors be reduced to a common basis. That is, if calculations are to be made on the basis of amperes per circuit, resistances and reactances must be expressed as ohms per circuit.

From data taken from Figs. 1 and 2, a series of calculations may be made whereby values of $V_t$ are found which will satisfy selected conditions of motor current and voltage. The load power factor and the speed are themselves determined by the motor characteristics. Any change in motor characteristics, as might be due to change in field strength or interpole-field shunting, will therefore require a separate series of calculations and will provide a different equipment characteristic for each set of motor characteristics.

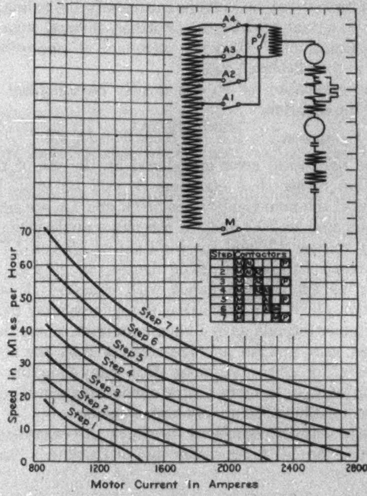

Fig. 5—Cross-Plotted Curves of Speed *vs.* Motor Current for Constant Open-Circuit Voltages

The actual calculation involves one step of presumably trial and error method. Referring to Fig. 3, the numerical value of $V_t$ may be calculated by the equation

$$V_t = \sqrt{(2\,V\cos\theta + IR)^2 + (2\,V\sin\theta + IX)^2}, \quad (1)$$

where

$V_t$ = transformer secondary open-circuit voltage
$V$ = motor voltage (here 2 motors are assumed in series, hence $2V$)
Cos $\theta$ = power factor
$I$ = current per motor
$R$ = total series resistance in ohms (transformer, coils, wiring, etc.)
$X$ = total series reactance in ohms (transformer, coils, wiring, etc.)

It will be noted that values of $R$ and $X$ are to be used in the calculation corresponding to the value of $V_t$ *to be calculated*. It, is necessary therefore, that $V_t$ first be estimated and corresponding values of $R$ and $X$ used in the calculation. After the first value of $V_t$ has been calculated, however, the value $V_t$ for other conditions of motor current or voltage can closely be estimated prior to actual calculation. Further, a small error in the estimate of $V_t$ does not introduce an appreciable error in the calculated value.

The calculation of $V_t$ can greatly be simplified by using the equation:

$$V_t \text{ (approx.)} = 2V + IR\cos\theta + IX\sin\theta \qquad (2)$$

The theoretical error introduced by the use of this equation rather than equation (**1**) will be small because (*a*) the numerical values of $IR$ and $IX$ are small as compared to $2V$, and (*b*) the phase angle between motor voltage $2V$ and the resultant of $IR$ and $IX$ is not great. In a set of actual figures run on a calculating machine in accordance with equation (**1**) and equation (**2**), it was found that the difference by using the simpler formula gave a maximum error of less than 0.5 per cent and an average error of 0.13 per cent. Actually, for computation by slide rule, equation (**2**) will be found to be more accurate than equation (**1**) due to less handling of relatively large numbers.

If the selected conditions for which the calculations are made are all for a certain motor current, a curve may be drawn showing the variations of speed with transformer open-circuit voltage at constant current. A family of such curves may be calculated and plotted as in Fig. 4. These curves may be used to determine what transformer taps are desired and, when such are determined, the speed *vs.* ampere characteristics of the equipment (Fig. 5) may be obtained by cross-plotting the curves of Fig. 4. Figs. 4 and 5 may also be used as the basis for determining other characteristics such as tractive effort *vs.* speed, speed *vs.* time, amperes *vs.* time, etc.

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## Discussion

**Walter H. Smith:** It would be desirable to know how near these theoretical calculations can be realized on a motor car or locomotive. My experience has been that such calculations serve only to tell what is desired but with so many variables to be encountered in a completed car or locomotive they can never be fully realized.

Traction type of transformers usually are designed for 15 to 20 volts per turn and for this discussion we will assume one with 16 volts per turn. The available voltage will then come in steps of 8 which may not suit the family of notching curves. If half turns are used it will throw some of the taps on the opposite end of the transformer. This may make a complicated cable or bus bar layout. Cable layouts on a motor car become a problem when cables as large as 1,100,000 cir mils are used. These cables have an overall diameter of some 2 in. and are required for the latest alternating-current traction motors.

Next are the contactors for changing voltages to the motors for acceleration. Too many notches will require a large number of these and their interlocking will become complicated.

A power circuit arrangement that utilizes a preventive coil is illustrated in Fig. 5. These coils tend to offset any theoretical curve arrived at. This can be minimized, however, with a properly designed coil.

It has been the writer's experience that with the motor, the control, the transformer and the equipment engineers to satisfy, these calculations must be a compromise for the completed car or locomotive for the best all round installation. Therefore the value of the calculations outlined in this paper is that an ideal arrangement can be established when planning such equipment.

# Operation of 3,000-Volt Locomotives
## On the Cleveland Union Terminals Electrification

BY F. H. CRATON* and H. W. PINKERTON†
Associate, A.I.E.E. Non-member

***Synopsis.***—*The operation of the 3,000-volt direct-current passenger locomotives on the Cleveland Union Terminals electrification has been studied after an initial period of service of more than two years. Twenty-two locomotives weighing 210 tons each are in service, normally handling passenger trains weighing 1,275 tons trailing over grades as high as 1.56 per cent.*

*During the two years over 1,000,000 miles of operation have been recorded, divided between about 410,000 miles per year for passenger service and 90,000 miles for switching. These figures indicate that the average performance in switching service is about two miles per hour, whereas the customary method of accounting credits switching locomotives with six miles per hour.*

*An analysis of the average time used for inspection and repairs shows an availability of 92 per cent. For the same period the utilization factor of 54 per cent is observed. The utilization factor will doubtless be improved with a resumption of normal traffic.*

*Data is given on energy consumption, both in road and in switching service, and curves are plotted showing the variation in energy consumption with different train weights. The all-day average in coach-yard switching is found to be about 85 kwhr per hour per locomotive, including auxiliaries, or a net average of about 55 kwhr per hour. Interesting records of brush wear, data on replacement of hub liners, wear on pantograph strips and condition of commutator and motor bearings are produced.*

*The record of failures for the two-year period of operation shows twelve engine delays of three or more minutes. Six of these were classed as electrical failures, giving 170,000 locomotive miles per failure. There were no failures due to mechanical causes or hot bearings in journals, traction motors or auxiliaries.*

*In addition to the energy consumption curves, speed-time-current curves for the Twentieth Century Limited, a profile of the line, main and auxiliary circuits for the locomotive, and characteristic curves are given.*

* * * * *

THE 3,000-volt direct-current electrification of the Cleveland Union Terminals Company has been in complete operation since June 29, 1930. The facility which attended the rapid transition from steam to electric operation with the opening of the new Union Station and the unusually successful performance of the equipment reflected the careful planning of the management. Not only the initial period of operation was comparatively trouble-free, but also the two years subsequently have witnessed successful performance. A few of the inevitable minor difficulties have come up and been corrected, but no trouble of fundamental importance has been encountered. It is the purpose of this paper to review briefly the design and characteristics of the locomotives selected for this work, and then to deal with the operation of these locomotives over the first two-year period of their service.

### PHYSICAL CHARACTERISTICS

Fig. 1 shows the profile of the electrified line from Collinwood to Linndale, involving about 17 route miles and 56 miles of track. New York Central passenger trains are electrically operated between Collinwood and Linndale, Big Four trains between the Union Station and Linndale, and Nickel Plate trains for about two miles on each side of the Union Station. Power is fed to the 3,000-volt d-c overhead contact line by two supervisory controlled substations of 18,000 kw total capacity.

### LOCOMOTIVES

The same locomotives are used in both switching and road service and hence all 22 units are identical. The conditions to be fulfilled by the locomotives very definitely fixed their general design. The necessity for starting a 1,275 ton train on the 1.56 per cent (1.63 per cent compensated for curvature) grade demanded a driver weight of about 300,000 lb. Negotiation of a 262-ft curve with train attached, called for a flexible running gear. The schedule requirements were covered by a typical run with a 1,275-ton train calling for a running time between Collinwood and Linndale, exclusive of stops, of 33 minutes westward and 30 minutes eastward. These requirements plus wheel-loading limitations and high-speed operation resulted in the design covered by Table I being adopted. The main and auxiliary circuits are shown in Fig. 2 and the characteristics of the locomotive are given in Fig. 3

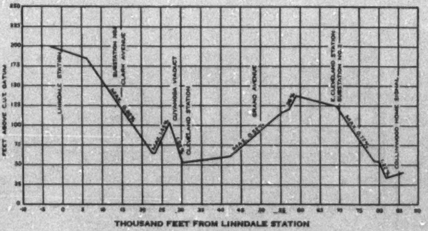

FIG 1—PROFILE

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*General Electric Co., Erie, Pa.

†Cleveland Union Terminals Co., Cleveland, Ohio.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

TABLE I—LOCOMOTIVE DATA

| *Weights* | Pounds |
|---|---|
| Total working order | 419,000 |
| On drivers | 312,000 |
| Per driving axle—average | 52,000 |
| Guiding | 107,000 |
| Per guiding axle—average | 26,750 |
| Total—light | 410,000 |
| Cab, platform and running gear | 265,780 |
| Traction motors (including gearing) | 72,880 |
| Other equipment | 71,340 |

| *Traction Motors* | |
|---|---|
| Number and type | 6 GE-278-C |
| Rated voltage | 1,500/3,000 |
| Method of drive | Twin gear—cushion type |
| Gear ratio | 74/27 = 2.741 |
| Ventilation | Forced |

*Locomotive Ratings—3,000 Volts*

| | One Hour—Blown | Continuous—Blown | |
|---|---|---|---|
| 120° C rise by res. | Full field (FS-1) | Full field (FS-1) | Rd. field (FS-3) |
| Tractive effort—lb | 30,600 | 25,500 | 19,200 |
| Coef. adhesion—% | 9.81 | 8.18 | 6.15 |
| Speed—mph | 37 | 38.5 | 51.5 |
| Horsepower | 3,030 | 2,635 | 2,635 |
| Amperes | 825 | 720 | 720 |

Tractive effort at 25% adhesion—78,000 lb

Maximum speed—70 mph

| | |
|---|---|
| Nomenclature | 2-C+C-2 419/312 6 GE-278-C—3.000 volts |
| Control | Type PCL (M.U.) 3 speeds full field 6 speeds reduced field |
| Current collector | 2 pantographs—sliding contact type |
| Braking | Air |
| Train heating equipment | Automatic oil fired steam boiler |

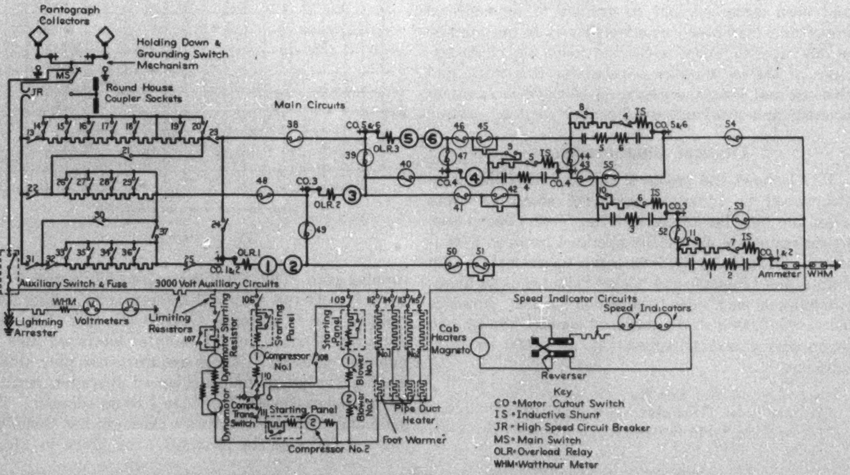
## LOCOMOTIVE OPERATION—ROAD SERVICE

Operation of electric passenger locomotives over a 17-mile line must involve use of the short time capacity of the electrical equipment if its full utility is to be realized. The operation of the Cleveland locomotives is based on this fact. Examination of the profile, Fig. 1, shows that both eastward and westward runs include several heavy grade sections. To handle the heavier trains on these portions of the line demands tractive efforts greatly in excess of the locomotive continuous tractive effort rating. In this respect the westbound run is the more severe.

The train covered by the Terminals Company Specifications consisted of 1,275 tons of steel passenger cars to be hauled between Collinwood and Linndale, with a ten minute stop at the Terminal, both eastbound and westbound, a two-minute stop at East Cleveland, both eastbound and westbound, and a stop of no duration on the three-degree and five-degree curves on Cuyahoga Viaduct, westbound only, with ten minute layovers at Collinwood and Linndale. Maximum running time exclusive of stops was specified as 33 minutes westbound and 30 minutes eastbound with an average line voltage of 2,700 and braking at 1.0 mphps.

In handling the specified train of 1,275 tons, or fifteen 85-ton cars, no restriction is placed on the use of intermediate (FS-2) or minimum (FS-3) traction motor field strength. By limiting the operation to intermediate field between Collinwood and the Terminal, and full field from the Terminal to Linndale, a train of nineteen 85-ton cars may be handled on the westward run with stops at East Cleveland and the Terminal, but omitting the Viaduct stop.

Fig. 4 gives an idea of train operation through the electric zone, being based on speed-current-time data



Pantograph Collectors
Holding Down & Grounding Switch Mechanism
MS
JR
Round House Coupler Sockets
Main Circuits
OLR.3
OLR.2
OLR.1
CO.5&6
CO.3
CO.4
CO.1&2
IS
Ammeter
WHM
Auxiliary Switch & Fuse
3000 Volt Auxiliary Circuits
Lightning Arrester
Voltmeters
Limiting Resistors
Dynamotor Starting Resistor
Starting Panel
Compressor No.1
Blower No.1
Blower No.2
Dynamotor
Comp. Trans. Switch
Compressor No.2
Cab Heaters
Pipe Duct Heater
Foot Warmer
Speed Indicator Circuits
Speed Indicators
Magneto
Reverser
Key
CO = Motor Cutout Switch
IS = Inductive Shunt
JR = High Speed Circuit Breaker
MS = Main Switch
OLR = Overload Relay
WHM = Watthour Meter

FIG. 2—MAIN AND AUXILIARY CIRCUITS FOR CLASS $2 - C + C - 2 - 419/312$ — 6GE278C, 3,000-VOLT PASSENGER LOCOMOTIVE, SCHEMATIC CONNECTION DIAGRAM. FOR CLEVELAND UNION TERMINALS CO., CLEVELAND, OHIO

taken on one section of "The 20th Century Limited" running westward from Collinwood to Linndale with one stop (at the Terminal). The train consisted of one electric locomotive hauling thirteen cars averaging 84.5 tons each, giving a trailing tonnage of 1,100. The specific conditions of this run are quite different from the contract requirements.

### LOCOMOTIVE OPERATION—SWITCHING SERVICE

Two locomotives are used in coach yard switching and three in regular passenger switching in the Station. Part of the coach yard trackage is on the Viaduct grade which makes it necessary to have the same weight on drivers for the switchers as for the road engines. To give added flexibility to the Terminal operation, it was thought desirable to have switching locomotives suitable for road service also. Hence all locomotives are identical and therefore available for any class of work on the Terminal property. The use of road locomotives in switching service has proved entirely practicable. The highly flexible running gear helps in this respect. Although the guiding truck centering device has high initial restraint, this decreases rapidly beyond about 1½-in. displacement of the bolster, thus keeping the guiding wheel flange wear to a minimum, even in the switching work where comparatively sharp curves are encountered. The locomotive has a three-speed control which gives 1/3 voltage per traction motor armature in the low-speed running connection. This permits switching movements to be made with a minimum of rheostatic losses consistent with the use of high-speed gearing.

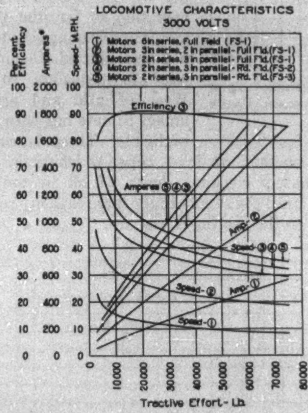


FIG. 3—LOCOMOTIVE CHARACTERISTIC CURVES

### OPERATING AND MAINTENANCE DATA

In the following discussion of the record of these locomotives to date, it should be understood that due allowance must be made for the limited time in service upon which the records are based. Twenty-two locomotives were purchased and went into complete revenue operation at the time of the initial changeover. At present, (October 12, 1932) three locomotives are in storage due to decline in traffic, the remaining nineteen being in regular service as heretofore. The Terminals Company has kept a very complete service and maintenance record on all locomotives since the beginning of operation, and the following data are based on this record.

*Mileage.* The total mileage for all locomotives for the first two years of operation was slightly over 1,000,000. For the year 1931, the following locomotive mileages were recorded:

| | |
|---|---|
| Passenger revenue miles | 412,410 |
| Switching miles in station and coach yard | 89,428 |
| Total revenue miles | 501,838 |
| Work train service miles | 650 |
| Total locomotive miles | 502,488 |

The switching mileage in the above tabulation is actual odometer miles, and is reported as such because of accounting requirements of the Terminals Company. It is usual practise, however, to report switching mileage at 6 mph, which would raise this item from 89,428 to 262,800 miles. In other words, the actual switching mileage in this case is equivalent to only 2.04 mph. Based on 6 mph for switching, the total revenue miles is 675,860 or 30,700 revenue miles per locomotive per year, as compared with about 22,800 revenue miles per locomotive per year based on odometer switching miles. The annual unit mileage will increase with an upturn in traffic. During the early months of operation in 1930, the locomotive mileage was at the rate of about 30,000 per unit per year, including switching miles as measured by odometer.

*Availability.* There are no actual availability data but a reasonably close estimate can be made. There is an average of two locomotives in the shop for regular monthly inspection and for repairs. These are actually under repair or inspection 48 hours each per week, making a total of 96 hours. In addition, each locomotive in service requires a daily inspection, followed by minor repairs, if required, which averages about 1½ hours per locomotive, or 189 hours per week for an average of 18 locomotives dispatched each day. This makes 96 plus 189, or 285 total actual out-of-service hours per week for inspection and maintenance. Based on this, the availability is 92 per cent.

*Utilization Factor.* Based on the actual hours for which crews were paid, the locomotives were in service 104,555 hours during the year 1931. Of this total, 43,800 hours were operated in switching service and the remaining 60,755 hours in road service. The total locomotive hours for 1931 being 22 × 365 × 24 = 192,720, the utilization factor was 54.2 per cent. Although this is a very good showing, the utilization will be markedly improved with more traffic.

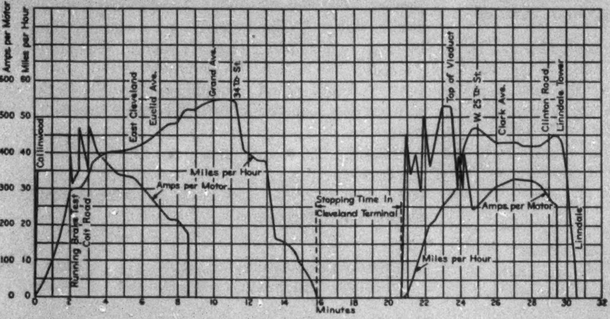


Fig. 4—Speed-Current-Time Curves for "The 20th Century Limited" from Collinwood to Linndale, Dec. 2, 1931. Trailing Tons, 1,100. Cleveland Union Terminals Electrification

*Energy Consumption.* The results of energy consumption tests in road movements between Linndale and Collinwood are plotted in Fig. 5. The test trains consisted of cars averaging 82 tons each. The values given are average watthours per trailing ton mile for the complete run from Collinwood to Linndale and *vice versa*, with stops at E. Cleveland and the Terminal in both cases. Curves are based on maximum schedule speed consistent with observance of all speed restrictions.

A number of observations of energy consumption in switching service has been made. It has been found that for the two locomotives in the coach-yard switching, where the work is almost continuous, the all day average is about 85 kwhr per hour per locomotive, including auxiliaries. Subtracting auxiliary power gives a net all day average of about 55 kwhr per hour to the traction motor circuits for this work. In the regular train switching in the station, the all day average is about 65 kwhr per hour including auxiliaries, three locomotives being assigned to this. However, this work is of an intermittent nature, which accounts for the lower power consumption. The all day average to the traction motor circuits in this service is about 40 kwhr per hour although the maximum hour is comparable with the coach yard average work. These figures compare with 50 to 60 kwhr per hour to the traction motor circuits in heavy freight switching as determined by tests on the New York Central and the Delaware, Lackawanna & Western.

*Brush Wear.* From present available data, traction motor brush life will vary between a minimum of 50,000 miles and a maximum of 100,000. As so many of the original brushes are still in service, definite figures cannot be given yet.

*Hub Liner Replacement.* In 1931, 110 hub liners were replaced. About 75 per cent of these were on the drivers and 25 per cent on the guiding wheels. No mileage records have been set up for hub liner replacement.

*Pantograph Strip Wear.* In operating trains in 1931, both pantographs were used, making a total of eight strips (copper) in use simultaneously on each locomotive. Average mileage per replacement was about 8,000.

*Traction Motor Overhaul.* Owing to the limited period of operation so far, the traction motor overhauling schedule has not been started. Commutator wear is negligible to date. Wear of axle and armature linings to date has been almost negligible. These bearings are of the constant oil level type, which maintain an approximately constant depth of oil in the waste chamber until the supply in the large capacity reservoir adjacent to the bearing is used up.

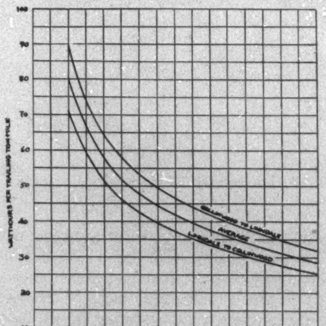


Fig. 5—Energy Consumption Curves

*Failures.* In the first two-year period of operation, there were twelve engine failures causing delays of three or more minutes. Six of these were classed as man failures, due largely to the inexperience of the crews in handling the new equipment. The other six were classed as electrical failures, giving about 170,000 locomotive miles per electrical failure. There were no failures due to mechanical causes nor were there any cases of hot bearings in either journals, traction motors, or auxiliaries.

In the winter of 1931-1932, unforeseen trouble was experienced due to unseasonable lightning storms, which on four occasions caused minor damage to the electrical circuits while the lightning arresters were out of service.

It is proposed to remedy this condition by operating arresters (aluminum cell type) throughout the winter and provide means for heating them to prevent freezing of electrolyte.

### ACKNOWLEDGMENT

The authors wish to thank Mr. H. D. Jouett of The Cleveland Union Terminals Company for making available the data upon which this paper is based, as well as for valuable criticism of the original manuscript. Thanks are extended also to Mr. H. A. Currie of the New York Central Railroad for much helpful comment.

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## Discussion

**F. H. Craton:** The Cleveland Union Terminals electrification went into complete operation on June 29th, 1930. For several weeks prior to that date, some of the locomotives were run in non-revenue service for the purpose of breaking in crews. During the 2½ years subsequently, various data on operation have been collected. The authors realize that it is still rather early to be able to present a comprehensive picture of the Cleveland operation for the reasons that the estimated future traffic conditions upon which the set-up was based have not as yet been realized except for a very brief period in 1930 and also that the maintenance cycle has not yet had a complete rotation. In addition to presenting the available operating data, we have pointed out briefly the general features of the locomotive design and how the requirements of the work to be done determined within rather close limits the design selected. The latter point is covered because there have been occasional inquiries as to why the $2 - C + C - 2$ design was adopted in preference to a construction using a concentration of power on fewer axles with greater weight per axle.

With the specified train of 1,275 tons trailing, an adhesive weight of approximately 150 tons was necessary. This makes available about 14 lb per ton tractive effort for acceleration at 25 per cent adhesion on the viaduct grade, giving a reasonable margin for poor rail conditions. To secure this weight and still meet track and bridge loading requirements, necessitated a long wheel base using at least six driving axles. Because of the sharp curves to be negotiated, a flexible running gear was necessary. For the speeds specified it was considered necessary to use a four-wheel guiding truck at each end of the locomotive.

While in general the mechanical design of the locomotive follows conventional lines, there is one feature that is novel. This is the characteristic of the gravity restraint device used for centering the guiding truck bolster. This is mentioned very briefly in the paper. In order to negotiate the sharp curves, a swing bolster is used with a 7 in. swing either way. The bolster is centered by rockers and specially shaped pads which rest and roll on the rockers. The value of the centering force required to act against displacement from a central position is chosen to guide the front end of the locomotive on tangent track and amounts to about 35 per cent of the load on the bolster. To avoid lurching of the locomotive when entering curves at speed, this force is increased to 42½ per cent at a displacement of 1¼ in. With displacement beyond this value, the centering force decreases to a final value of 7½ per cent for a displacement of 7 in. In using this type of characteristic, advantage is taken of the fact that the amount of guiding action required for a symmetrical articulated running gear on sharp curves is much less than necessary on straight track because when fully in the curve, the articulation guides the two main trucks. The use of this characteristic gives desirable tracking qualities, especially by elimination of high flange wear on sharp curves. This is of particular advantage in the switching service because the locomotives assigned to switching are on sharp curves a relatively large percentage of the time.

The application of these locomotives to this service is an example of the use of the overload capacity of this type of equipment. Although these locomotives have sufficient capacity to handle main line, high speed passenger service over a comparatively level profile, their use with 15 to 19 car trains over the Cleveland profile requires the use of their overload capacity to an unusual extent. Reference to Fig. 4 will show this even though the train under consideration is not up to full tonnage. In normal operation, these locomotives develop frequent peaks of 6,000 hp at the rail, with extended periods at 4,000 to 5,000 hp. While there is no novelty in the locomotives developing these outputs, the use of overload operation throughout practically the entire "power on" period is not so common.

# Power Supply for Main Line Railway Contact Systems

BY P. A. McGEE* and E. L. HARDER†
Non-member Associate, A.I.E.E.

***Synopsis.**—The general system problem encountered in the supply of power for electric traction is dealt with through a study of the performance of the principal available systems. The paper is confined to the electrical characteristics and consequent capacity and spacing requirements. The first part describes the performance of systems in electrical terms and requires no assumptions as to the magnitude of train loads. Index figures are developed for specifying concisely the characteristics considered, and curves are given for determining substation loads and catenary rms current and regulation. The second part provides a perspective of power system requirements with various systems through a general study of distribution and transmission based on a number of assumed train loads. Fleets of trains of equal size and uniform spacings are made the basis for the generalized solution of the distribution and transmission problems as well as for the study based on specific load conditions. The essential electrical dimensions of most of the heavy traction electrifications of the world are tabulated.*

* * * * *

## INTRODUCTION

IN the first part of the paper the characteristics of the systems considered are presented in electrical terms. This is the more general specification since it precludes the necessity of assumptions by the authors as to magnitudes of loads. Any load may be specified and the resulting requirements determined from the data given.

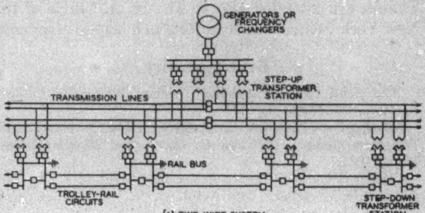
This material will be particularly useful in the early design stages of new electrifications, where it is necessary to compare, on the basis of specific traffic conditions and known locations of reliable power supply, the relative merits of the several systems. There are, however, numerous cases, such as extensions, changes, future growth studies, and the checking of existing situations in which the material presented will be of use to those connected with present electrifications.

In the second part the various available systems are compared on the basis of several assumed loading conditions varying from light present day loads to loads representative of possible future conditions. The results are in terms of kva or kw loads and permissible station spacings in miles. This general study and the tabulation of data on existing systems provides the best perspective, from a railway point of view, of the requirements with various systems of electrification.

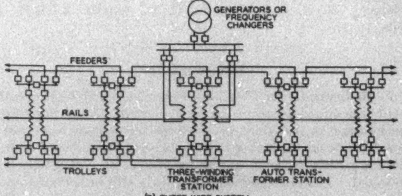
*Systems Considered.* The systems considered are:

| | |
|---|---|
| 600 volt d-c third rail | 12-24-36 kv, 25 cycle, three-wire |
| 1,500 volt d-c catenary | 24-48-72 kv, 25 cycle, three-wire |
| 3,000 volt d-c catenary | 12-66 kv, 25 cycle, two-wire |
| | 12-132 kv, 25 cycle, two-wire |

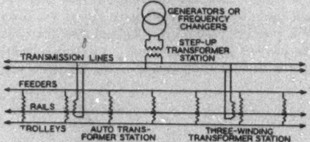
Fig. 1 shows the two-wire system, the three-wire system and the three-wire system with transmission. The contact line arrangement considered in the d-c system is similar to that in Fig. 1A except in the general study where consideration is given to paralleling contact lines midway between substations. Although data are not given specifically for the three-wire system with transmission, the transmission lines may be treated as for a two-wire system and the remainder as a three-wire system.


GENERATORS OR FREQUENCY CHANGERS
STEP-UP TRANSFORMER STATION
TRANSMISSION LINES
RAIL BUS
TROLLEY-RAIL CIRCUITS
STEP-DOWN TRANSFORMER STATION

(A) TWO-WIRE SYSTEM


GENERATORS OR FREQUENCY CHANGERS
FEEDERS
RAILS
TROLLEYS
THREE-WINDING TRANSFORMER STATION
AUTO TRANS-FORMER STATION

(B) THREE-WIRE SYSTEM


GENERATORS OR FREQUENCY CHANGERS
STEP-UP TRANSFORMER STATION
TRANSMISSION LINES
FEEDERS
RAILS
TROLLEYS
AUTO TRANS-FORMER STATION
THREE-WINDING TRANSFORMER STATION

(C) THREE-WIRE WITH TRANSMISSION SYSTEM

FIG. 1—A-C SUPPLY SYSTEMS

*Loading Conditions.* Railway transmission and distribution systems are generally laid out to accommodate some maximum traffic congestion which may be a recorded or assumed normal daily or seasonal occurrence or an abnormal condition caused by traffic disar-

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†General Engineer, Westinghouse Elec. & Mfg. Co.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

rangement. In any case this maximum movement may be represented by a fleet consisting of trains dispatched at regular intervals at a certain speed for a given length of time. The power supply system should be designed to give satisfactory operation with a certain amount of apparatus out of service. In this paper it has been assumed that the system must operate satisfactorily with one element out of service, such for example, as one transmission circuit.

## ELECTRICAL CHARACTERISTICS OF SUPPLY SYSTEMS

The *distribution system* consisting of track substations and contact lines may be considered separately from the *transmission system* which carries power from the generating or supply points to the track substations.

In the a-c systems, distribution and transmission are not entirely independent. A certain amount of through transmission takes place over the trolley-rail circuits, and in the three-wire system the trolley conductors are common to the transmission (trolley-feeder) and distribution (trolley-rail) circuits. However, as will be shown later, these factors may be accounted for by corrections with reasonable accuracy. With this provision, the regulation and heating problems of distribution and transmission may be considered separately.

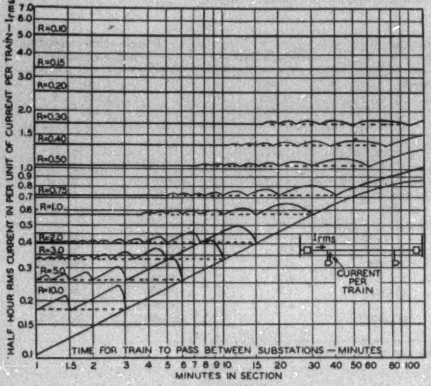


FIG. 2—CURRENT IN TROLLEY AT SUBSTATION BUS

$$R = \frac{\text{Train spacing}}{\text{Substation spacing}}$$

It is assumed that the indicated train density lasts in a section for one-half hour

## DISTRIBUTION

*Load Data.* Typical load data and general information regarding train energy consumption, transmission and converting efficiencies, together with system load factors and substation plant factors as employed in the second part of the paper are shown in Table I.

TABLE I—LOAD AND SYSTEM DATA

| | Suburban | Terminal and tunnel | Main line |
|---|---|---|---|
| Yearly power consumption in U.S.A. Millions of kw-hr per single-track mile per year | 0.13–0.6 | 0.5–1.7 | 0.15–0.65 |
| Installed substation capacity in U.S.A. per single-track mile | 300–400 kw | 400 kw avg | 120 kw to 670 kva |
| System load factor—U.S.A | 24%–30% | 14%–32% | 21%–58% |
| Substation plant factor—U.S.A | 7%–15% | 12%–27% | 9%–33% |
| Average power factors at generating stations or supply points, for maximum load conditions | | | |
| A-c systems | 72%-78% | | 80%–85% |
| D-c systems | 90%–100% | | 90%–100% |

| | | |
|---|---|---|
| Average power factor at trolley bus due to train loads as indicated, for maximum load conditions. A-c systems | Local suburban | 80% |
| | Express suburban | 85% |
| | Combined | 82% |
| | Main line | 90% |

APPROXIMATE POWER CONSUMPTION AT SUBSTATION TROLLEY BUS FOR BOTH D-C AND A-C SYSTEMS

| | | Watt-hours per ton-mile |
|---|---|---|
| *Local suburban including car heating and auxiliaries | | 105 |
| *Express suburban including car heating and auxiliaries | | 70 |
| Freight, 30 miles per hr on level track | 2,500 ton trains | 27 |
| | 5,000 ton trains | 23 |
| | 10,000 ton trains | 19 |
| Passenger, 60 mph incl. train auxiliaries, on level track | 1,000–1,500 ton trains | 40 |
| | 2,000 ton trains | 38 |

| | |
|---|---|
| Average frequency changer losses | 5%–10% |
| Average losses in a-c system from frequency changer to trolley bus | 7% |
| Average losses in d-c contact lines | 10% |
| Losses in a-c contact lines | 1.5–6% |

D-c locomotives approximately 5% more efficient than a-c locomotives

| | |
|---|---|
| Load cycle upon which substation converting or transforming equipment is rated | 100% continuous<br>150% 2 hrs.<br>300% swing<br>(5 min. for transformers) |

Generators for a-c systems are either maximum rated or rated on the basis of 100% continuous, 150% for one hour.

Approximate factors by which substation loads calculated on the basis of trains drawing average load continuously, must be increased to obtain rms effect of accelerating and coasting.

| | |
|---|---|
| Local suburban | 20% |
| Express suburban | 10% |
| Freight and passenger | 0% |

Average trolley bus voltage under severe regulation conditions. (Assumptions used in general study.)

| | |
|---|---|
| D-c | flat regulated |
| 12-kv a-c system | 10,500 volts |
| 24-kv a-c system | 21,000 volts |

*Combinations used in suburban trains consist of a four-motor car geared for safe speed of 70 mph with trailer.

*Contact Line Currents.* With a regular movement of trains over a contact section, the rms current flowing in the contact system at one end for any interval of time is a function of the total amperes per train, substation spacing, train spacing, train speed, and the number of trains in the fleet. Assuming the fleet to cover the contact line section for nearly half an hour, the one-half hour rms current may be read directly from Fig. 2. This chart may be used in several ways. If the substation spacing has been fixed by other factors, the chart gives the current upon which the contact line conductivity must be based. Table II lists the current carrying capacity of some typical contact lines. The

TABLE II—CONTACT SYSTEMS

*A-c Contact System*

| No. | Conductivity millions circular-mils | Amperes continuous current capacity 50° C rise: Avg. tarnished conductors | Ampere-miles to produce 1,200-volt drop at 25 cycles (10% regulation on 12-kv system, 5% on 24-kv system): Power Factors 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|
| 1 | 0.328[1] | 720 | 2,950 | 2,980 | 3,100 | 3,350 | 5,100 |
| 2 | 0.367 | 760 | 2,700 | 2,800 | 2,920 | 3,240 | 5,500 |
| 3 | 0.438 | 1,000 | 3,070 | 3,140 | 3,300 | 3,700 | 6,200 |
| 4 | 0.467[1] | 860 | 3,160 | 3,250 | 3,450 | 3,860 | 6,650 |
| 5 | 0.605 | 1,330 | 3,430 | 3,540 | 3,780 | 4,250 | 7,650 |
| 6 | 0.616 | 1,120 | 3,260 | 3,380 | 3,600 | 4,120 | 7,700 |
| Averages | | | 3,095 | 3,177 | 3,360 | 3,745 | 6,480 |
| Maximum departures of one item from average | | | +11 | +11 | +13 | +13 | +18 |
| | | | −13 | −12 | −13 | −13 | −21 |
| Average for 70, 80 and 90% power factor | | | | | 3,500 ± 20% | | |

Table based on one trolley—two track circuit.
Multiply regulation (or divide amp-mi) by 1.04 for one trolley—one track circuit.
Multiply by 0.96 for one trolley—four track circuit.
Multiply regulation by approx. 1.16, 1.32 and 1.48 respectively if one, two or three other trolleys carry the same current.

*D-C Contact Systems Used in General Study*

| Type | Conductivity millions cir mils | Current capacity amperes | Voltage class | Ampere-miles to produce 10% regulation |
|---|---|---|---|---|
| 3rd rail | 2.36 | Heating not limit | 600 | 1,150 |
| Aerial | 1.029 | 1,340 | 1,500 | 1,730 |
| Aerial | 1.029 | 1,340 | 3,000 | 3,460 |

*Compositions of Catenaries Used Above*

| No. | Messenger: Size inches | Messenger: Conductivity cir mils | Aux. messenger: Size gage | Aux. messenger: Conductivity cir mils | Contact wire: Size gage | Contact wire: Conductivity cir mils | Total conductivity cir mils |
|---|---|---|---|---|---|---|---|
| 1 | 0.625 | 211,600 | | | 4/0 | 116,500 | 328,100 |
| 2 | 0.625 | 38,800 | 4/0 | 211,600 | 4/0 | 116,500 | 366,900 |
| 3 | 0.628 | 55,260 | 2-2/0 | 266,000 | 4/0 | 116,500 | 437,760 |
| 4 | 0.818 | 350,000 | | | 4/0 | 116,500 | 466,500 |
| 5 | 0.750 | 65,700 | 2-4/0 | 423,200 | 4/0 | 116,500 | 605,400 |
| 6 | 0.888 | 500,000 | | | 4/0 | 116,500 | 616,500 |
| D.C | | 586,000 | 4/0 | 211,600 | | 232,000 | 1,029,000 |
| 100 lb rails used throughout | | | | | | | |

[1] 0.467 millions cir mils and 0.328 millions cir mils used in Table V for 12-kv and 24-kv trolleys.

one-half hour rms current should not appreciably exceed the continuous capacity of the lines.

If the spacing of substations is to be determined the chart may be used as a basis for drawing curves of catenary current *vs.* substation spacing for any fleet dimensions. These would be considered along with the several other factors affecting substation spacing.

*Correction for Through-Feed in A-C Systems.* In a-c systems allowance must be made in the trolley size for through-feed, or power fed through a section to the sections beyond. In the two-wire system the through-feed over the trolley-rail generally is small enough to neglect in comparison with the maximum local distribution currents. The amount may be computed from the maximum load beyond the section, the number of trolleys, and the distribution of through-feed indicated in Table III.

When the three-winding transformers of the three-wire system are designed with low impedance from the generator to the trolley-feeder circuit, the distribution of through-feed will be very nearly as given in Table III. However, the relative proportions of through-feed for a considerable distance from the supply point may be altered by a different proportioning of the three-winding transformer impedances. In any case, the

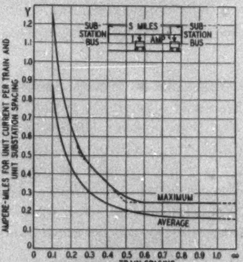


FIG. 3—AMPERE-MILES FROM SUBSTATION BUS TO TRAIN AS TRAIN MOVES THROUGH SECTION = *YIS*

Based on equal substation bus voltages

through-feeds at transmission and at distribution voltages when expressed in amperes, added, and divided among the available trolleys seldom exceed 30 to 50 per cent of the local distribution currents.

*Contact Line Regulation.* Two regulation figures are of importance, namely, the maximum regulation to a train near the center of a section, and the average regulation to a train as it progresses through a section from one end to the other. The corresponding maximum and average ampere-miles are plotted on a unit basis in Fig. 3 for uniform train movements. This regulation chart, similar to the heating chart described above, may be used either to determine the regulations, maximum and average, corresponding to an assumed substation spacing, train current, speed and spacing, and contact system; or to determine the substation spacing limits for given fleet dimensions with various assumed contact systems.

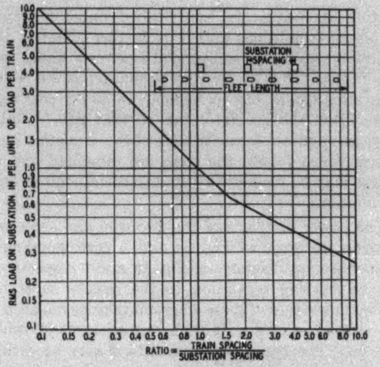


Fig. 4—Substation Load Due to a Fleet Movement of Trains

Rms applies to period while the fleet covers the two sections adjacent to a substation. For the additional times required for the first and last trains to pass through two sections, the rms is from 0.5 to 1 times the value given by the curve. Curve does not apply for fleets less than two substation spacings in length

Table II lists the number of ampere-miles of contact-system current necessary to produce 10 per cent regulation with the a-c and d-c systems. The regulation will, of course, vary in direct proportion to the ampere-miles. It will be observed that in the a-c system, conductivity variations of from 0.328 to 0.616 million circular mils change the ampere-miles required to produce 10 per cent regulation by not over 13 per cent from mean values for the usual power factors. Thus the mean values may be used with a fair degree of accuracy. This makes it possible with a-c systems to determine substation spacing limits from a regulation standpoint independent of the conductor size used.

The table further shows that for the power factors usually encountered, namely, 70 to 90 per cent, the average regulation index varies from the upper and lower limits by 20 per cent or less. This index figure of regulation on a 25-cycle, 12-kv trolley-rail circuit may be stated as 350 trolley ampere-miles ± 20 per cent for each one per cent of regulation with power factors of 70 to 90 per cent and conductivities from 0.328 to 0.616 million circular mils. The average value, 350, corresponds to 80 per cent power factor and 0.467 million circular mils.

*Substation Loads.* The chart of Fig. 4 is given for determining the rms load at substations due to fleet movements of trains on one or more tracks. The substation loads may be determined separately for each track and the results added to obtain the total substation loads. This procedure assumes an unfavorable stagger of trains on different tracks such as to throw simultaneous peaks on the substations. The load resulting from a favorable stagger of trains may be obtained by considering two tracks together and using a single fleet of twice the density.

Thus, for example, consider duplicate fleets moving in the same direction on two tracks. For two fleets of trains at substation spacings the total load is 2.00. For a single fleet of trains at half of substation spacing the load is also 2.00. There is no difference due to staggering when the trains in a fleet are at substation spacings or less. For two fleets of trains at twice substation spacings the total load is 1.15 and when combined into a single fleet of trains at substation spacings the load becomes 1.00, indicating a 15 per cent difference in the hour load depending on the stagger. This difference will be found to be greater as the train spacing increases.

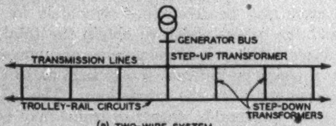
## TRANSMISSION

*General Considerations.* With d-c contact systems the transmission lines will normally consist of three-phase circuits. As the characteristics of these circuits are well known they are not included in this paper and only transmission circuits of the a-c systems will be considered.

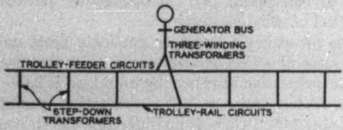
With all contact systems a large spacing of power supply points causes an improved load factor and more economical generation with larger units and it is, in consequence, generally desirable to feed a maximum number of track substations from one source of power.

Extensive electrifications fed by generating stations at intervals present two types of situations which may be represented by Figs. 5d and 5e. Fig. 5d represents a maximum condition of regulation where the two supply points are electrically tied together. Fig. 5e represents a maximum condition of regulation with the transmission system sectionalized so that the supply points feed stub end to the midpoint between them. The difference in the permissible spacing from the regulating standpoint, between the tied through and the sectionalized transmission systems will depend upon the maximum fleet lengths. If these extend the total distance between the points of power supply the spacing will be the same under both conditions.

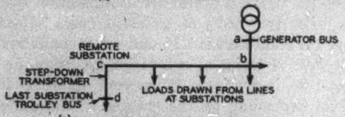
It will be observed that because of symmetry the system of Fig. 5d could be cut apart in the center without altering regulation or heating, with the fleets in the positions shown. It would then represent two stub ends, each feeding fleets of half the length of the fleets shown. From this we conclude that to each stub end distance permissible with fleets of given lengths there corresponds a permissible generating station spacing twice as great with fleets twice as long.


GENERATOR BUS
STEP-UP TRANSFORMER
TRANSMISSION LINES
TROLLEY-RAIL CIRCUITS
STEP-DOWN TRANSFORMERS

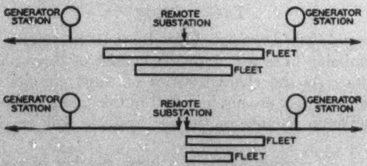
(a) TWO-WIRE SYSTEM


GENERATOR BUS
THREE-WINDING TRANSFORMERS
TROLLEY-FEEDER CIRCUITS
STEP-DOWN TRANSFORMERS
TROLLEY-RAIL CIRCUITS

(b) THREE-WIRE SYSTEM


a
GENERATOR BUS
REMOTE SUBSTATION
c
b
STEP-DOWN TRANSFORMER
LOADS DRAWN FROM LINES AT SUBSTATIONS
LAST SUBSTATION TROLLEY BUS
d

(c) EQUIVALENT DIAGRAM FOR DETERMINING REGULATION AT REMOTE SUBSTATION


GENERATOR STATION
REMOTE SUBSTATION
GENERATOR STATION
FLEET
FLEET
GENERATOR STATION
REMOTE SUBSTATION
GENERATOR STATION
FLEET
FLEET

(d AND e) LOAD CONCENTRATIONS FOR MAXIMUM REGULATION

FIG. 5—POWER DIAGRAMS

The maximum condition of loading on a particular source occurs when the fleets are grouped with their centers opposite that source.

*Heating of Conductors.* The curves of Fig. 6a show the amperes and kva per circuit which may be transmitted with 50 deg C rise in single-phase aerial lines. These data together with the number of circuits and the proportions of through-feed over the transmission circuits given in Table III indicate the total kva which may be fed in one direction from a supply point.

*Regulation.* In the regulation studies that follow it is assumed that the generating, transforming and converting apparatus are fully loaded under maximum regulation conditions and it is further assumed that generators are over-compounded 5 per cent under these conditions. Thus 25 per cent regulation at the remote substation trolley bus corresponds to 30 per cent regulation from the generator bus to that point. While these assumptions form the basis of the regulation index figures which follow, the steps are tabulated and the figures may be readily corrected to correspond to other assumptions.

TABLE III—PROPORTION OF THROUGH-FEED IN TRANSMISSION CIRCUITS OF A-C RAILWAY NETWORKS
(Remainder flows over trolley-rail circuit)

| System kv | Trolleys and tracks | Transmission lines or feeders | % transmission circuit through-feed |
|---|---|---|---|
| 12-66 | 2 | 1 | 90 |
| 12-66 | 2 | 2 | 95 |
| 12-66 | 4 | 3 | 94 |
| 12-66 | 4 | 4 | 97 |
| 12-132 | 2 | 1 | 97 |
| 12-132 | 2 | 2 | 99 |
| 12-132 | 4 | 3 | 98.5 |
| 12-132 | 4 | 4 | 99 |
| 12-24-36 | 2 | 1 | 91 |
| 12-24-36 | 2 | 2 | 103 |
| 12-24-36 | 4 | 3 | 101 |
| 12-24-36 | 4 | 4 | 100 |
| 24-48-72 | (Approximately same as 12-24-36 kv) | | |

Based on 4-0 transmission conductors and 0.328 million cir mil trolleys.

Division of power flow is based on line impedance only—influence of transformer impedances not considered.

The power diagrams of the two-wire and three-wire systems are given in Fig. 5a and b corresponding to the connection diagrams of Fig. 1A and B respectively. For considering regulation to the remote substation trolley bus, either of these diagrams may be replaced by the simple series circuit with tapped loads shown in Fig. 5c. The regulation from *a* to *d* may be divided into three parts, namely, step-up transformer regulation *a* to *b*, transmission line regulation *b* to *c*, and step-down transformer regulation from *c* to *d*.

The regulations at full load in transformers of normal designs for railway systems are given in Fig. 6b, and the line regulations per million kva miles in Fig. 6c and d for the two-wire and three-wire systems respectively. On the basis of these data Table IV has been constructed giving the very important index figures, of transmission possible with each type of system. The number of kva-miles permissible is the best single measure of the system's ability to transmit power with satisfactory regulation. For example, a 132-kv circuit can supply 3.7 million kva-miles. This may consist of 37,000 kva over 100 miles, or 18,500 kva over 200 miles, or a uniformly distributed load of 740 kva per mile for 100 miles or any other combination of load and distance that totals 3.7 million kva-miles. Kva-miles may be converted to permissible generating station spacing by placing the fleets in the worst regulation location and from the corresponding substation kva loads, calculating the cumulative kva-miles along the line from the remote substation until the permissible value is reached.

TABLE IV—TRANSMISSION POSSIBLE WITH TWO-WIRE AND THREE-WIRE SYSTEMS
In Millions of Kva-Miles for 25% Regulation at Last Substation Trolley Bus

| | Transformer regulation | | | 2 track 1 transmission circuit | | 4 track 3 transmission circuits | |
|---|---|---|---|---|---|---|---|
| System kv | Step up % | Step down % | Permissible line regulation % | % Regulation per m-kva-mi | Permissible m-kva-mi | % Regulation per m-kva-mi | Permissible m-kva-mi |
| 12–132 | 6.8 | 3.2 | 20.0 | 5.4 | 3.7 | 1.8 | 11.1 |
| 12–66 | 5.6 | 3.2 | 21.2 | 21.0 | 1.0 | 7.0 | 3.0 |
| 24–48–72 | 5.6 | 2.2 | 22.2 | 12.8 | 1.7 | 4.9 | 3.7 |
| 12–24–36 | 3.2 | 1.4 | 25.4 | 51.0 | 0.5 | 19.6 | 1.3 |

Based on 4/0 copper transmission conductors.
Trolley conductivity 328,000 circular mils.
25% regulation, 5% overcompounding of generator bus, 30% regulation from generator bus to last substation trolley bus.
80% average power factor at transmission lines.

*Correction for Through-Feed in Trolley-Rail Circuit.* In the two-wire system the kva-miles computed on the basis of 100 per cent transmission over the transmission circuit may be corrected by multiplying by the percentages given in Table III. In the three-wire systems in which transmission voltage is three times distribution voltage, power flow produces nearly the same drop in the transmission circuit whether it flows in that circuit or in the trolley-rail. Hence, for regulation purposes, it may all be assumed to flow in the transmission circuit. However, this phenomena is due to a close equality between trolley-feeder self-impedance and trolley-rail—trolley-feeder mutual-impedance and where this relation is not fulfilled a correction can be made. The relatively small amount of trolley-rail through-feed in a normal arrangement makes this correction generally unnecessary.

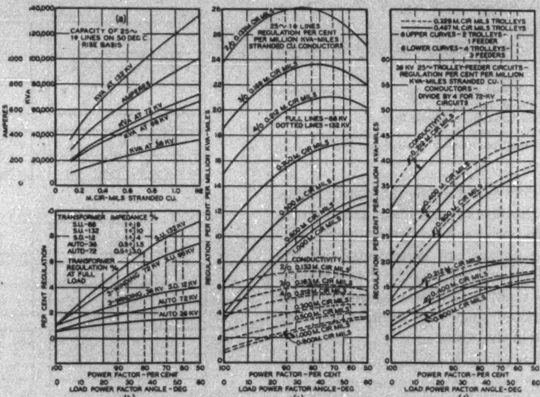


FIG. 6—SINGLE-PHASE TRANSMISSION SYSTEMS—DATA

## Study of Power System Requirements with Light, Medium, and Heavy Traffic

This section comprises a study in which on the basis of assumed loading conditions and assumed conductor sizes, the substation spacing limits, substation loads, and generating station spacings and loads are developed. The loading conditions cover a sufficient range to include the present day traffic on existing electrifications as well as the heavier traffic which trends indicate for the future.

The study is organized into three parts according to the type of traffic, *viz.*; suburban motor car trains, main line freight trains and main line passenger trains. The study for suburban trains is entirely separate and complete in itself while in the studies of main line freight and passenger trains, passing fleets of the two types are assumed in determining substation and generating station capacity requirements and permissible generating station spacings. The results of the study are given in Table V supplemented by the station spacing curves of Figs. 8 and 9.

*Definition of a Fleet.* The fundamental element considered is a fleet of similar trains moving on one track. A given fleet contains trains of only one type, such as freight, or passenger, all moving at the same average speed and spaced at regular intervals.

Substation spacing limits due to regulation and to heating of the assumed contact lines are first developed for each fleet. Substation loads contributed by individual fleets are given corresponding to the limiting spacing of substations. And finally combinations are formed by combining fleets on different tracks.

*Premises.* The basic load data used have been tabulated in Table I, and the contact line sizes and characteristics in Table II. The assumptions as to number of trains in a fleet, and train size with each class of traffic, and the train speeds and spacing assumed, are indicated in the first few items of the table describing the study, namely, Table V.

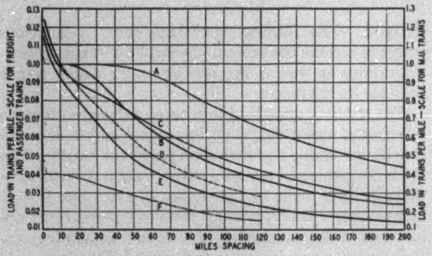


Fig. 7—Rms Loads at Feeding Points per Mile of Track for Train Schedules as Shown in Table V (Each Track Considered Separately)

Rms is for 1-hour period except three-train passenger fleet = one-half hour

Curves
- *A*—freight—10-train fleet
- *B*—freight—5-train fleet
- *C*—passenger—6-train fleet
- *D*—local multiple unit—37-train fleet
- *E*—passenger—3-train fleet
- *F*—express multiple unit—21-train fleet

*Load Curves.* Load curves at feeding points of various spacings, for each of the fleets considered, are given in Fig. 10. They apply to both generating station and substation loads. These curves are constructed on the basis of a division of load inversely as the distance from stations. This is the most pessimistic assumption for the a-c generating stations since load division between stations is controllable in that case.

From a consideration of these curves in the light of the usual load cycles* used for substation converting equipment ratings and generator ratings, the one-hour load has been found to be the most significant single load. (One-half hour for short passenger train fleets.) Equipment which provides for this load will stand the higher peaks of shorter duration. The one hour loads have, therefore, been plotted in Fig. 7 and form the basis for the loads given in Table V.

## DISTRIBUTION

*Substation Spacing Limits.* Substation spacings may be limited by either heating or regulation. In general, both limits are given, it being understood that the lower of the two values actually represents the permissible spacing. Spacing limits with d-c system are given in Table V for tracks paralleled and in Fig. 8 for tracks not paralleled.

*Contact Line Regulation.* An average regulation of 10 per cent has been taken as the limiting value. The corresponding spacings listed in Table V are based on third rail and catenary sizes, indicated in Table II. As shown previously, conductivity variation of the a-c trolley within reasonable limits does not effect regulation materially. In the d-c system regulation varies almost directly with contact line conductivity, and the return is assumed to be through a pair of 100 lb running rails. For the a-c systems the regulation is given on the basis of a two-track road although the regulation is within 4 per cent of that for single or four-track roads.

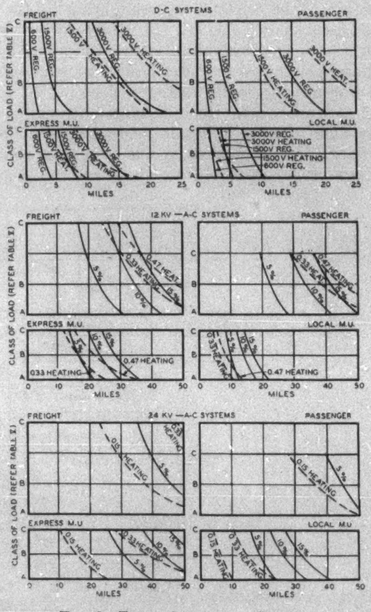


Fig. 8—Track Substation Spacings

As limited by 50 deg C temperature rise of aerial and by average regulation. Figures on heating curves indicate trolley conductivity in millions of cir mils. Percentages are average regulations

*Contact Line Heating.* The heating limits given in the table correspond to the trolley sizes mentioned in Table II. In addition the heating limits corresponding to smaller a-c trolleys, namely, 0.15 and 0.33 million circular mils for 24 kv and 12 kv trolleys respectively are plotted in Fig. 8. No allowance is made for through-feed current in the case of three-wire systems. This

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*Given in Table I.

TABLE V—FLEET DIMENSIONS AND POWER REQUIREMENTS

Suburban motorcar trains

| Item | Class load<br>Type service<br>No. of trains in fleet | Light-*A*<br>Local<br>37 | <br>Express<br>21 | Medium-*B*<br>Local<br>37 | <br>Express<br>21 | Heavy-*C*<br>Local<br>37 | <br>Express<br>21 |
|---|---|---|---|---|---|---|---|
| 1 | No. of cars per train | 6 | | 10 | | 14 | |
| 2 | Train weights in tons | | | | | | |
| | 600 v d-c | 348 | | 580 | | 812 | |
| | 1,500 v d-c | 378 | | 630 | | 882 | |
| | 3,000 v d-c | 408 | | 680 | | 952 | |
| | 12,000 v a-c | 408 | | 680 | | 952 | |
| | 24,000 v a-c | 420 | | 700 | | 980 | |
| 3 | Avg. speed mph | 25.0 | 37.5 | 25.0 | 37.5 | 25.0 | 37.5 |
| 4 | Train interval, miles | 1.0 | 2.5 | 1.0 | 2.5 | 1.0 | 2.5 |
| | minutes | 2.4 | 4.0 | 2.4 | 4.0 | 2.4 | 4.0 |
| 5 | Kw avg. per train at substa. | | | | | | |
| | 600 v d-c | 900 | | 1,500 | | 2,100 | |
| | 1,500 v d-c | 991 | | 1,652 | | 2,312 | |
| | 3,000 v d-c | 1,075 | | 1,800 | | 2,520 | |
| | 12,000 v a-c | 1,075 | | 1,800 | | 2,520 | |
| | 24,000 v a-c | 1,104 | | 1,840 | | 2,576 | |
| 6 | Substa. spacing limits[3] mi. | | | | | | |
| | 600 v d-c[5] | 4.5*r* | 5.2*r* | 2.9*r* | 4.0*r* | 2.2*r* | 3.1*r* |
| | Two-track systems[4] 1,500 v d-c[5] | 6.5*h* | 16.3*h* | 3.9*h* | 9.7*h* | 2.8*h* | 7.0*h* |
| | 3,000 v d-c[5] | 11.9*h* | 29.8*h* | 7.1*h* | 17.8*h* | 5.1*h* | 12.8*h* |
| | 12,000 v a-c | 13.4*h* | 30.0*r* | 8.0*h* | 21.2*h* | 5.5*h* | 15.3*h* |
| | 24,000 v a-c | 24.0*h* | 56.0*r* | 14.4*h* | 38.2*h* | 10.3*h* | 27.3*h* |
| | Four-track systems[6] 600 v d-c[5] | 4.8*r* | | 3.7*r* | | 3.0*r* | |
| | 1,500 v d-c[5] | 9.3*h* | | 5.5*h* | | 4.0*h* | |
| | 3,000 v d-c[5] | 17.0*h* | | 10.2*h* | | 7.3*h* | |
| | a-c | (Same as two-track local) | | | | | |
| 7 | Corres. substa. hour loads Kw per single-track mi. | | | | | | |
| | Two-track systems[4] 600 v d-c | 675 | 247 | 1,125 | 414 | 1,570 | 580 |
| | 1,500 v d-c | 745 | 263 | 1,240 | 454 | 1,730 | 633 |
| | 3,000 v d-c | 790 | 260 | 1,350 | 475 | 1,890 | 684 |
| | 12,000 v a-c | 765 | 260 | 1,350 | 463 | 1,890 | 675 |
| | 24,000 v a-c | 691 | 200 | 1,310 | 405 | 1,930 | 637 |
| | Four-track system[6] 600 v d-c | 460 | | 770 | | 1,075 | |
| | 1,500 v d-c | 510 | | 850 | | 1,185 | |
| | 3,000 v d-c | 518 | | 925 | | 1,290 | |
| | 12,000 v a-c | 530 | | 925 | | 1,295 | |
| | 24,000 v a-c | 482 | | 905 | | 1,320 | |

Transmission study based on a 35-mile block of uniformly distributed load.

| Item | Class load | Light-*A′* and *A* | | Medium-*B* | Heavy-*C* |
|---|---|---|---|---|---|
| 8 | Kw per single-track mile | 250 | 575 | 906 | 1,290 |
| 9 | Gen.—Sta. loads[7] kw per single-track mile | | | | |
| | Two-track system 12-24-36 kv | 89 | 287 | 680 | 1,050 |
| | 24-48-72 kv | 78 | 180 | 284 | 404 |
| | 12-66 kv | 78 | 180 | 387 | 645 |
| | 12-132 kv | 78 | 180 | 284 | 404 |
| | Four-track system 12-24-36 kv | 78 | 250 | 567 | 968 |
| | 24-48-72 kv | 78 | 180 | 284 | 404 |
| | 12-66 kv | 78 | 180 | 284 | 526 |
| | 12-132 kv | 78 | 180 | 284 | 404 |

Freight trains

| Item | Class load<br>No. of trains in fleet | Light-*A*<br>5 | <br>10 | Medium-*B*<br>5 | <br>10 | Heavy-*C*<br>5 | <br>10 |
|---|---|---|---|---|---|---|---|
| 1 | Wt. of train ex. locomotive, tons | 2,500 | | 5,000 | | 10,000 | |
| 2 | Average speed, mph | 30 | | 30 | | 30 | |
| 3 | Train interval, miles | 10 | | 10 | | 10 | |
| | minutes | 20 | | 20 | | 20 | |
| 4 | Kw avg per train at substa. | 2,000 | | 3,500 | | 5,700 | |
| 5 | Substa. spacing limits[3] mi. | | | | | | |
| | Two-track[8] 600 v d-c[5] | 2.5*r* | | 2.4*r* | | 1.4*r* | |
| | 1,500 v d-c[5] | 7.2*r* | | 4.4*r* | | 3.0*r* | |
| | 3,000 v d-c[5] | 21.6*r* | | 15.0*r* | | 11.3*r* | |
| | 12,000 v a-c | 43.5*r* | | 34.5*r* | | 26.0*r* | |
| | 24,000 v a-c | — | 86*r* | — | 66*r* | 51.0*r* | |
| 6 | Substa. kw[9] per S.T.M. for above spacings. 2 or 4-track[8], frt. and pass. | | | | | | |
| | 600 v d-c | 235 | 247 | 390 | 403 | 592 | 607 |
| | 1,500 v d-c | 218 | 225 | 365 | 381 | 557 | 580 |
| | 3,000 v d-c | 194 | 206 | 326 | 337 | 485 | 501 |
| | 12,000 v a-c | 141 | 190 | 266 | 324 | 435 | 483 |
| | 24,000 v a-c | 86 | 145 | 175 | 275 | 310 | 441 |
| 7 | Gen. sta. loads[10], kw per S.T.M. Combined freight and passenger[8] | | | | | | |
| | Two-track system 12-24-36 kv | 72 | 147 | 138 | 273 | 240 | 455 |
| | 24-48-72 kv | 44 | 92 | 80 | 173 | 133 | 308 |
| | 12-66 kv | 44 | 120 | 107 | 205 | 170 | 337 |
| | 12-132 kv | 44 | 82 | 72 | 135 | 109 | 214 |
| | Four-track system 12-24-36 kv | 62 | 141 | 157 | 278 | 252 | 456 |
| | 24-48-72 kv | 44 | 82 | 67 | 167 | 116 | 288 |
| | 12-66 kv | 44 | 87 | 70 | 177 | 156 | 314 |
| | 12-132 kv | 44 | 82 | 66 | 135 | 108 | 208 |

Passenger trains

| Item | Class load<br>No. of trains in fleet | Light-*A*<br>3 | <br>6 | Medium-*B*<br>3 | <br>6 | Heavy-*C*<br>3 | <br>6 |
|---|---|---|---|---|---|---|---|
| 1 | Wt. of train ex. locomotive, tons | 1,000 | | 1,500 | | 2,000 | |
| 2 | Average speed, mph | 60 | | 60 | | 60 | |
| 3 | Train interval, miles | 10 | | 10 | | 10 | |
| | minutes | 10 | | 10 | | 10 | |
| 4 | Kw avg per train at substa. | 2,400 | | 3,600 | | 4,600 | |
| 5 | Substa. spacing limits[3], mi. | | | | | | |
| | Two-track[11] 600 v d-c[5] | 3.4*r* | | 2.4*r* | | 1.9*r* | |
| | 1,500 v d-c[5] | 10.0*r* | | 9.0*r* | | 6.8*r* | |
| | 3,000 v d-c[5] | 32.5*r* | | 25.0*r* | | 20.5*r* | |
| | 12,000 v a-c | 42.0*r* | | 33.0*r* | | 29.0*r* | |
| | 24,000 v a-c | — | 79*r* | — | 65*r* | — | 57*r* |
| 6 | Substa. kw[9] per S.T.M. above spacing. | | | | | | |
| | Two track[11] | 126 | 124 | 198 | 207 | 257 | 270 |
| | | 108 | 114 | 165 | 176 | 225 | 240 |
| | | 78 | 107 | 130 | 170 | 184 | 225 |
| | | 66 | 93 | 113 | 148 | 160 | 195 |
| | | 40 | 68 | 72 | 115 | 101 | 157 |
| 7 | Gen.-sta. loads | (See freight table above) | | | | | |

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[3] *h* = heating limit of 50° C rise in avg tarnished conductors.
*r* = 10% regulation. Contact systems described in Table II.

[4] Load on second track = 25% of that on fully loaded track.

[5] D-c contact systems paralleled midway between substa. in this case.

[6] Third and fourth tracks loaded 25% of fully loaded express and local tracks.

[7] Based on spacings given in Fig. 9 for generating stations interconnected, except that upper spacing limit is 120 miles.

[8] Second track is a passenger train load of the same class.
Four-track load is two freight and two passenger fleets.

[9] One hour loads used except for 3-train passenger fleets—half hour.

[10] Based on spacings given in Fig. 9 for generating stations except that upper spacing limit is 240 miles.

[11] Second track is unloaded.

factor may be accounted for by additions to the conductivity required for local distribution as outlined in a previous section.

An inspection of the results shows that for aerial lines used heating is the limitation with most suburban multiple-unit train loads and regulation with main line freight or passenger loads. For the third rail, regulation is the only limitation.

*Substation Capacity.* Substation rms loads are given corresponding to the limiting spacings. Local and express suburban loads are increased by 20 per cent and 10 per cent respectively from the loads read on the load curves to account for the rms effect of accelerating and coasting. The required substation capacity, without allowance for spare capacity, is approximately half of the hour load except for the 10-train freight fleets for which the continuous capacity must be about 75 per cent of the hour load. Less spare capacity would be required with the a-c system because of the relatively greater ability to draw on the spare capacity in adjacent stations.

### TRANSMISSION

From the substation loads determined in the distribution study, the next step is the determination of permissible generating station spacings and consequent loads. As before, both heating and regulation limits must be considered. The general plan adopted for this study is that of determining the conductor size, for each case, at which heating and regulation limits are equivalent. This plan has the advantage of defining the fields where regulation or heating respectively are limiting.

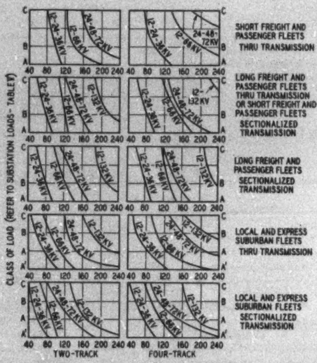

FIG. 9—GENERATING STATION SPACINGS FOR 25 PER CENT REGULATION

Through and sectionalized transmission are illustrated in Fig. 5 (d and e), short and long fleets are respectively, freight, 5 and 10 trains, passenger, 3 and 6 trains. Conductor sizes used will carry the load current. One transmission line or feeder considered in service with two-track systems. Three transmission lines or feeders considered in service with four-track systems

For spacings smaller than those tabulated, heating will be the limit, and with sufficient conductivity to carry the current, the regulation will be less than 25 per cent. Also if the conductivity listed is divided into more circuits the regulation will be less than 25 per cent for the same spacing. A minimum conductor size of 4/0 copper and a maximum of 1.750 million circular mils were considered although as pointed out the larger sizes are not practical and more circuits would be used instead of the extreme conductor sizes. An arbitrary upper limit of generating spacing was taken as 240 miles for main line and 120 miles for suburban systems.

In the case of suburban loads an additional loading condition lighter than the light main line load was included to indicate the possibilities on lightly loaded branches. In general, combinations of express and local multiple unit train loads are considered in the study of transmission for suburban systems, and combinations of freight and passenger train fleets for the main line electrification.

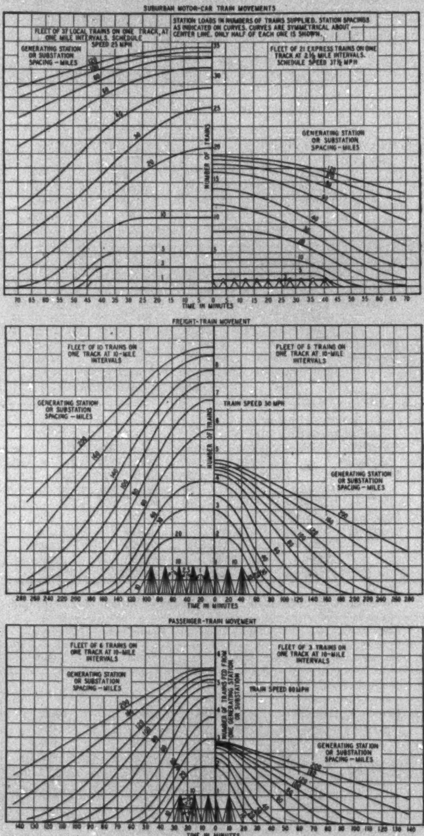

FIG. 10—LOAD CURVES

TABLE VI—ELECTRIC RAILWAY POWER STATISTICS

| Type of transportation | | Railway | Year | Contact system | Miles route | Miles single track main line | Approx. million ton mile /annum | Million kw-hr/annum | | Max. kw demand generated or at pt. of supply | Load factor 365 days at pt. of supply % | Installed sub-station kw or kva | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Generated or at pt. of supply | Delivered to contact lines | | | Total | Per route mile | Per s.t. mile |
| Suburban | | *U.S.A.* | | | | | | | | | | | | |
| | | Delaware Lackawanna & Western | 1931 | 3,000v d-c | 69 | 133 | 551.00 | 48.54 | 41.15 | 22,903 | 24.4 | 40,000 | 580 | 300 |
| | a | Illinois Central | 1929–30 | 1,500v d-c | 38 | 113 | 615.00 | 68.22 | 59.87 | 29,617 | 26.2 | 46,500 | 1,225 | 411 |
| | b g k | Long Island | 1929 | 650v d-c | 135 | 323 | 2,360.00 | 203.30 | 165.68 | | | 130,000 | 964 | 403 |
| | p c | P.R.R. Phila. Paoli | 1929 | 11,000v a-c | 36 | 114 | 281.00 | 49.49 | | | | 39,000 | 1,082 | 342 |
| | p | Reading | 1931–32 | 11,000v a-c | 65 | 148 | 183.00 | 19.16 | | 7,840 | 28.0 | 42,000 | 645 | 284 |
| | d | Staten Island | 1929 | 600v d-c | 22 | 43 | 156.00 | 16.70 | | 6,473 | 29.5 | 13,000 | 591 | 303 |
| | | *Argentine* | | | | | | | | | | | | |
| | e | Buenos Aires Western | 1929 | 800v d-c | 23 | 63 | 431.00 | 49.78 | 27.72 | 21,000 | 27.0 | | | |
| | e | Central Argentine Rwy | 1929 | 800v d-c | 43 | 80 | 402.00 | 34.65 | 28.52 | 12,500 | 31.6 | | | |
| | | *Australia* | | | | | | | | | | | | |
| | e | N.S.W. Govt. Rwys | 1929 | 1,500v d-c | 88 | 220 | 1,645.00 | 136.01 | 117.95 | 45,000 | 34.5 | | | |
| | e k | Victorian Govt. Rwys | 1929 | 1,500v d-c | 167 | 343 | 1,830.00 | 175.73 | 103.85 | 48,000 | 41.7 | 71,400 | 426 | 208 |
| | | *Germany* | | | | | | | | | | | | |
| | e | Berlin Suburban | 1929 | 800v d-c | 145 | 286 | | 248.30 | | 70,000 | 40.5 | 153,000 | 1,050 | 535 |
| | | Hamburg Suburban | 1929 | 6,000v a-c | 20 | 42 | | 43.70 | 34.90 | 17,000 | 29.3 | | | |
| | | *India* | | | | | | | | | | | | |
| | d | B.B. & C.I. Rwy | 1929 | 1,500v d-c | 21 | 60 | 444.00 | 36.65 | | 11,328 | 37.0 | 20,000 | 954 | 333 |
| | | *Japan* | | | | | | | | | | | | |
| | g | Tokio Suburban | 1929 | 1,200v<br>1,500v d-c | 65 | 130 | 1,720.00 | 138.93 | 117.58 | 28,400 | 55.6 | 74,000 | 1,140 | 570 |
| | | *Netherlands* | | | | | | | | | | | | |
| | | Netherlands Rwy | 1929 | 1,500v d-c | 84 | 168 | 855.00 | 48.10 | | | | | | |
| | | *United Kingdom* | | | | | | | | | | | | |
| | e | L.N.E. Rwy | 1929 | 600v d-c | 32 | 68 | 246.00 | | 13.58 | | | 10,000 | 313 | 147 |
| | e | London & Suburbs | 1929 | 600v d-c | 38 | 76 | 741.00 | 82.27 | 59.56 | 21,360 | 44.0 | 25,650 | 676 | 338 |
| | | Southern Rwy | 1929 | 600v d-c | 270 | 710 | 3,275.00 | 273.94 | 229.06 | 75,000 | 41.6 | 105,500 | 289 | 148 |
| Terminal & tunnel operation | | *U.S.A.* | | | | | | | | | | | | |
| | c | B. & O. Baltimore | 1929 | 600v d-c | 3.6 | 7.2 | 74 | 7.34 | 5.88 | 6,000 | 14.0 | | | |
| | a | Boston & Maine Hoosac Tunnel | 1929 | 11,000v a-c | 8.0 | 16.0 | 191 | 7.76 | 7.66 | | | 7,500 | 938 | 469 |
| | | Cleveland Union Terminal | 1929 | 3,000v d-c | 17.0 | 40.0 | | | | | | 15,000 | | 375 |
| | c | Michigan Central Detroit | 1929 | 600v d-c | 4.5 | 9.0 | 99 | 12.69 | 7.15 | | | | | |
| | c | N.Y.C. N.Y. Terminal | 1929 | 650v d-c | 63.0 | 214.0 | 1,710 | 196.52 | 164.63 | 69,790 | 32.2 | 80,000 | 1,270 | 374 |
| | c g q | P.R.R. Manhattan Transfer | 1929 | 675v d-c | 13.0 | 50.0 | | | 85.09 | | | 36,000 | 2,770 | 720 |
| | | *Canada* | | | | | | | | | | | | |
| | a | Canadian National St. Clair Tunnel | 1929 | 6,600v a-c | 3.6 | 7.3 | 112 | 6.24 | 4.41 | 4,000 | 17.8 | 2,860 | 795 | 392 |
| Main line | | *U.S.A.* | | | | | | | | | | | | |
| | d | Butte Anaconda & Pacific | 1929 | 2,400v d-c | 37 | 37 | 254 | 20.40 | | 9,579 | 24.4 | 7,000 | 189 | 189 |
| | c | C.M. St. Paul & Pacific H to Avery | 1929 | 3,000v d-c | 441 | 441 | 2,311 | 107.99 | 69.07 | | | 59,500 | 135 | 135 |
| | c | C.M. St. Paul & Pacific O to Seattle | 1929 | 3,000v d-c | 218 | 230 | 800 | 44.24 | 26.70 | | | 28,000 | 128 | 121 |
| | c h | Great Northern | 1929 | 11,000v a-c | 73 | 73 | 404 | 28.19 | 21.33 | 15,000 | 21.4 | 27,000 | 370 | 370 |
| | c | N.Y. N.H. & H.R.R. N.Y. to Woodlawn | 1929 | 650v d-c | 12 | 48 | 372 | 22.70 | 18.40 | | | | | |
| | h | N.Y. N.H. & H.R.R. S.P. Lines | 1929 | 11,000v a-c | 116 | 382 | 4,036 | 208.47 | 169.21 | 41,000 | 58.0 | 91,000 | 785 | 238 |
| | | Norfolk & Western | 1929 | 11,000v a-c | 64 | 152 | 871 | 83.40 | 68.94 | 32,000 | 29.7 | 56,000 | 875 | 368 |
| | i | P.R.R. Phila to Westchester | 1931 | 11,000v a-c | 26 | 49 | | | | | | 33,000 | 1,295 | 674 |
| | | P.R.R. Wil. to Trenton | 1931 | 11,000v a-c | 58 | 230 | | | | | | 93,000 | 1,610 | 404 |
| | | P.R.R. Trenton to Sunnyside | 1931 | 11,000v a-c | 68 | 256 | | | | | | 90,000 | 1,322 | 351 |
| | r | Virginian | 1929 | 11,000v a-c | 135 | 157 | 1,878 | 109.97 | 100.58 | 49,000 | 25.6 | 97,500 | 723 | 621 |
| | | *Austria* | | | | | | | | | | | | |
| | e | Innsbruck, Fel, Bregenz | 1929 | 15,000v a-c | 132 | 132 | 868 | | 38.00 | | | | | |
| | | *Brasil* | | | | | | | | | | | | |
| | j | Paulista | 1929 | 3,000v d-c | 204 | 217 | 646 | | 33.44 | | | 25,000 | 122 | 115 |
| | | *Chile* | | | | | | | | | | | | |
| | | Chile State | 1929 | 3,000v d-c | 144 | 180 | 449 | | 33.95 | 6,193 | 62.5 | 20,000 | 139 | 111 |
| | | *France* | | | | | | | | | | | | |
| | j k | Midi | 1929 | 1,500v d-c | 575 | 918 | 1,155 | 327.47 | 86.29 | 60,000 | 62.3 | 106,000 | 185 | 115 |
| | l | P.L.M. | 1930 | 1,500v d-c | 84 | 167 | | | | | | 36,000 | 430 | 215 |
| | d | P. & O. | 1929 | 1,500v d-c | 148 | 404 | 3,400 | 137.00 | 106.70 | 28,000 | 55.9 | 52,000 | 351 | 129 |
| | | *Germany* | | | | | | | | | | | | |
| | m | Bres., Gorlitz, & Br. | 1929 | 15,000v a-c | 216 | 348 | 1,227 | 69.88 | 58.54 | 26,000 | 30.6 | 28,000 | 129 | 80 |
| | m | Mag. Lpzg., Halle | 1929 | 15,000v a-c | 118 | 232 | 999 | 61.20 | 40.00 | 15,000 | 46.5 | 19,000 | 161 | 82 |
| | m | Bav. Munich | 1929 | 15,000v a-c | 434 | 700 | 2,283 | 126.10 | 116.70 | 33,000 | 43.6 | 70,000 | 161 | 100 |
| | m | Baden Basel | 1929 | 15,000v a-c | 30 | 30 | 72 | 8.51 | 5.21 | 1,750 | 55.5 | 4,000 | 133 | 133 |
| | | *India* | | | | | | | | | | | | |
| | | G.I.P. | 1929 | 1,500v d-c | 128 | | | 31.03 | 26.48 | | | | | |

TABLE VI—*Continued*—ELECTRIC RAILWAY POWER STATISTICS

| Type of transportation | Railway | Year | Contact system | Miles route | Miles single track main line | Approx. million ton mile /annum | Million kw-hr/annum | | Max. kw demand generated or at pt. of supply | Load factor 365 days at pt. of supply % | Installed sub-station kw or kva | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Generated or at pt. of supply | Delivered to contact lines | | | Total | Per route mile | Per s. t. mile |
| Main line | *Italy* | | | | | | | | | | | | |
| | f Genoa, Cev., Leghorn.... | 1929 | 3,700v 3P | 331 | 540 | 1,572 | 144.50 | | | | 47,000 | 142 | 87 |
| | f Turin, Modane Ronco.... | 1929 | 3,700v 3P | 205 | 345 | 1,182 | 103.00 | | | | 27,000 | 132 | 78 |
| | f Florence Bologna........ | 1929 | 3,700v 3P | 88 | 110 | 407 | 45.00 | | | | | | |
| | *Japan* | | | | | | | | | | | | |
| | g Tokio to Yokozuka....... | 1929 | 1,200v<br>1,500v d-c | 120 | 222 | 850 | 45.75 | 37.75 | | | 42,800 | 424 | 193 |
| | *Mexico* | | | | | | | | | | | | |
| | b The Mexican............ | 1929 | 3,000v d-c | 64 | 64 | 120 | 15.18 | 14.43 | | | 9,000 | 140 | 140 |
| | *Morocco* | | | | | | | | | | | | |
| | Moroccan Rwy.......... | 1929 | 3,000v d-c | 149 | 149 | 351 | | 14.28 | | | | | |
| | *Sweden* | | | | | | | | | | | | |
| | n Riksgrensen, Kir. & Luela | 1929 | 16,000v a-c | 287 | 287 | | | | | | 43,000 | 150 | 150 |
| | Stockholm Gothenburg... | 1929 | 16,000v a-c | 286 | 353 | | | | | | 28,800 | 100 | 82 |
| | *Switzerland* | | | | | | | | | | | | |
| | Swiss Federal............ | 1929 | 15,000v a-c | 1,076 | 1,612 | 6,564 | 472.85 | 394.00 | 100,000 | 53.9 | 270,000 | 253 | 167 |
| | *Union of So. Africa* | | | | | | | | | | | | |
| | o Pietersburg to Glencoe... | 1929 | 3,000v d-c | 171 | 230 | 1,765 | 104.69 | | 24,300 | 49.1 | 44,000 | 257 | 191 |

a Average loaded passenger car taken at 60 tons.
b Average loaded passenger car taken at 55 tons.
c Average loaded passenger car taken at 66 tons.
d Average loaded passenger car taken at 52 tons.
e Average loaded passenger car taken at 48 tons.
f Average loaded passenger car taken at 42 tons.
g Certain substations supply another system.
h Installed substation kw includes allowance for direct feed to contact lines of three winding stations and power plants.
i Installed substation kw. Note provision made for practically double the capacity shown.
j Ton miles are for freight only.
k Generated power supplied to other users.
l Installed substation kw. Note provision made for 48,000 kw.
m Passenger train weight taken at 250 tons.
n Traffic density varies between 2 million and 7 million ton miles per mile of track per annum.
o Ton miles, energy consumption and maximum demand values taken from Mr. F. Lydall's paper I.E.E., March 1928.
p Electrification layout provides for main line operation.
q Lines to be changed to a-c operation and included in comprehensive main line electrification.
r Provision to convert contact lines to 24,000 volts. Substation kw includes three winding and auto transformer capacity.

It is assumed that there are three transmission lines or three feeders and four trolleys in service with the four-track system, and one transmission line or one feeder and two trolleys in service on the two-track system.

## LOAD FACTORS

Knowing the average load over any number of days, a quantity which may be easily approximated when the total tonnage movement on a railway is known, the load-factor for the road with any spacing of power supply feed points may be estimated from the load curves for various train and fleet sizes.

As an example, the following conditions may be assumed. A road may move a given freight tonnage over a single track in one direction with ten 5,000-ton trains, or five 10,000-ton trains operating in fleets with trains at 10-mile intervals. These freight train fleets may be assumed to pass passenger train fleets of six 1,000-ton trains and three 2,000-ton trains respectively in such a manner as to place a maximum load on a point of power supply. The effect of this maximum load on feeding points located at 10-mile, 100-mile and 200-mile intervals will be considered. If we assume that the average power demand over a period of 12 months is of the order of 65 kw per single track mile, or 130 kw per two-track mile, (the average for one large system) the following tabulation employing values taken from Fig. 10 shows the variation in load-factor due to variation of supply point spacing and train size. The values for train power demand for the four train sizes are taken from Table V.

| Spacing between feeding points | No. of trains in fleet | Kw demand 1-hr and ½-hr basis | Avg kw 365 days | Load factor 365 days |
|---|---|---|---|---|
| 10 miles..... | 10 F. 6 P....... | 5,780........ | 1,300........ | 22.5% |
| 10 miles..... | 5 F. 3 P....... | 9,850........ | 1,300........ | 13.2% |
| 100 miles..... | 10 F. 6 P....... | 37,400........ | 13,000........ | 34.8% |
| 100 miles..... | 5 F. 3 P....... | 37,400........ | 13,000........ | 34.8% |
| 200 miles..... | 10 F. 6 P....... | 43,800........ | 26,000........ | 59.4% |
| 200 miles..... | 5 F. 3 P....... | 40.300........ | 26.000........ | 64.6% |

The principal point of interest brought out in this tabulation is the fact that any increase in train size with a given total tonnage movement tends to lower the load factor at feeding points relatively closely spaced, such as track substations; whereas, at points 100 and more miles apart, the load factor may be beneficially affected by an increase in train size.

## Data on Existing Systems

The essential electrical characteristics of most of the heavy traction electrifications of the world are given in Table VI. The ranges of yearly power consumption and installed substation capacities for the U.S.A. have been given in Table I. A few electrifications upon which data were not available at the time of publication have been omitted from the list.

### CONCLUSIONS

A general method has been presented for determining directly the approximate electrical characteristics of railway power supply systems, and important index figures have been developed which best specify the performance of the distribution and transmission facilities. The specification of maximum load conditions of an electrified railroad in terms of train fleet dimensions has been shown to be a practical and useful procedure in numerous instances. This plan has made possible the construction of general station-load curves, catenary-current curves and regulation curves which are presented in the paper.

The general study and data on existing electrifications provide a perspective of power system requirements for electrified railroads. They may be used as a basis for economic studies, and are at least a starting point in a general study of the ability of the various systems of the present day to handle the loads of the future.

Among the specific deductions that may be drawn from the material presented are the following:

1. There is little advantage, from the substation capacity standpoint, in spacing substations farther apart than trains.
2. In main-line service, where the train spacings are considerably greater than the required substation spacings with low-voltage systems, the required substation capacity is considerably less with high-voltage than with low-voltage contact lines.
3. With higher voltage contact lines the spare capacity in each substation is less due to the greater shifting of load to adjacent stations.
4. The use of railroad transmission lines greatly reduces the total demand which must be provided for by the power company, and makes it possible for the power company to provide for this demand in a few large units instead of numerous small ones. The load factor study in the paper indicates that the demand may be 1.5 to 2.5 times as great for substations at 10-mile intervals as for generating stations at 100-mile intervals. These factors would be increased for smaller substation spacings, with the same train fleets.

### ACKNOWLEDGMENTS

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## Discussion

**D. R. MacLeod:** So many economic factors control the layout of a power system to be used for a given electrification that it is almost impossible to cover the subject adequately with a theoretical investigation since any such investigation is only as accurate as the assumptions permit it to be. There are, however, certain basic principles that may be outlined.

The outstanding assumption in this paper is that of fleet movement of trains which we interpret as implying a very dense traffic movement. There is a question in the writer's mind as to how this assumption would fit a railroad having a varying profile and especially the electrification of a grade. In an actual investigation we assume that the authors would lay out the system on the basis of the normal load condition, using certain limiting assumptions for satisfactory normal operation and then check the system for the abnormal conditions that might arise, using the limits specified for satisfactory abnormal operation.

In Table II an index of regulation for a 25-cycle, 12-kv trolley rail circuit of 350 trolley ampere miles plus or minus 20 per cent for each 1 per cent of regulation is developed. Another index that is useful is the approximate impedance at 25 cycles of a single trolley with rail return. The resistance of the trolley usually is much greater than that of the rail even when the a-c resistance is taken as three times that of the d-c resistance due to skin effect. The reactance component is more dependent upon the distance of the contact wire above the track than on the sizes of wires or number of rails for the wire sizes, wire configuration and rail weights usually employed in main line work. A good approximate value to use is $0.2 + j\,0.4$ ohms per mile. Probably the only merit in choosing these figures is that they are easy to remember. They apply most nearly to systems having a 4/0 phono-electric contact wire and a 4/0 auxiliary, but tests on actual systems show such variations from calculated values that too much reliance should not be placed on their accuracy. Ground wires and other auxiliary return conductors affect the reactance values materially.

In the paragraph headed "Correction for Through-Feed in A-C Systems" the writer calls attention to the fact that in d-c systems using rectifiers or other sources of power supply that are not flat compounded there is through-feed from adjacent sections. In the case of three-winding transformers, the relative proportions of through-feed depend upon the relation of the impedances of the two circuits and therefore the effect that the three-winding transformer impedances will have upon the proportioning of through-feed will depend upon the relation of the transformer impedances to the rest of the system.

Under the heading "Transmission" and as conclusion 4 at the end of the paper, the statement is made that with all contact systems a large spacing of power supply points causes an improved load factor and more economical generation with larger units and it is in consequence generally desirable to feed a maximum number of track substations from one source of power. In 25-cycle, single-phase systems the size of unit must be selected in order to take care of rush hour loads and normal loads with the best load factor. Larger units of frequency changer sets are more efficient than smaller ones. Where the systems are tied together on the 60-cycle side of the frequency changer sets there is no problem of stability on the 25-cycle side, but the power supply points should be selected in such a way that maximum stability may result when examined from the 60-cycle side. Where the systems that supply power to the electrification are not tied together, or where individual steam or hydroelectric systems are the major sources of supply, single-phase stability must be examined.

It is interesting to note that the authors have presented data on 24-kv, 25-cycle systems. Higher voltages on the contact system have been under discussion for some time and they undoubtedly will be used if the need for them arises. The insulation of the transformers on the rolling stock, in view of existing space and weight requirements, would be the principal problem.

When determining the location of substations on a given a-c system, factors of an engineering nature such as inductive coordination, selectivity and discrimination of breakers, etc., must be considered. Using the index developed in connection with

Table II of the paper or the approximate value of impedance given in this discussion it is seen that an infinite source of power feeding one mile of trolley at 12 kv will give approximately 30,000 amperes when short-circuited. If the breakers are set at 2,000 amperes the substations can only be 15 miles apart and it is probable that regulation in the power feed would reduce this figure to about 12 miles. Where high speed breakers are used it is customary to provide back-up protection that operates on the impedance principle or equivalent and that will clear faults at a lower value in longer time. High speed protection is of great value in preventing burning down of wires and damage to apparatus. These breakers must not trip on switching surges which may be as high as four times the normal current rating of the transformers fed by the breakers.

Selectivity of breakers fed from an a-c bus is rendered more difficult the greater the through-feed. The greater the substation spacing the greater the through-feed, other things being kept constant.

**W. S. H. Hamilton:** In Table II the current carrying capacity of the contact system assumed for 3,000 volts d-c and having a total conductivity of 1,029,000 cir mils is given as 1,340 amperes. Based on the methods described by Messrs. Schurig and Frick in the *General Electric Review* of March 1930 and August 1931, the current carrying capacity for such contact system should be 2,065 amperes, instead of 1,340 amperes—an increase of 55 per cent. This increased current rating should mean an increase in substation spacing of approximately the same percentage where the text indicates that the limitation is heating rather than regulation.

In connection with the curves given in Fig. 8 for d-c substation spacing, it is stated in the text that these curves are based on tracks not paralleled while the d-c substation spacings given in Table V are based on tracks paralleled midway between substations only. In any d-c system, the regulation varies directly with the line conductivity and hence the paralleling is an important factor. Modern practise on d-c systems is to parallel oftener than this paper would indicate. For instance in the Cleveland Union Terminals electrification the trolleys are paralleled at each substation and circuit breaker house, a total of 8 points in the 17 miles, and the track return is paralleled oftener than this.

As an instance of how this affects the voltage drop, the writer has calculated the voltage drop at the locomotive for various conditions corresponding to the passenger train loading *B* shown in Table V for the condition of two trains symmetrically located between substations with substations 25 miles apart. While this condition does not give the maximum drop it indicates very clearly the effect that paralleling of the trolleys between substations has on the voltage drop.

CONTACT SYSTEM TIES BETWEEN SUBSTATIONS

| | 0 | 1 | 2 |
|---|---|---|---|
| Single track | 756 | | |
| Double track | 756 | 530 | 422 |
| Four tracks | 756 | 416 | 254 |

The contact system tie stations with 3,000 volts d-c are relatively inexpensive and the high speed breakers used are positive and simple in operation. It is good practise anyway to tie the trolleys together at each major interlocking plant.

Since the curves in Fig. 8 apparently are based on single track conditions only, they seem to the writer to be misleading particularly when heavier classes of loading are considered. For instance no one would operate a fleet of 37 electric trains all in one direction on single track, and when this is set up on a four-track basis with proper allowance made for contact system paralleling the substation spacing would be much greater than that shown.

In Table V the average kw per train at the substation (which presumably is at the substation outgoing bus) seems very high for these trains when hauled by d-c locomotives.

| | Light A | Medium B | Heavy C |
|---|---|---|---|
| **Freight Trains** | | | |
| Given by authors | 2,000 | 3,500 | 5,700 |
| Calculated | 1,600 | 2,600 | 3,400 |
| **Passenger Trains** | | | |
| Given by authors | 2,400 | 3,600 | 4,600 |
| Calculated | 1,700 | 2,500 | 3,350 |

While the authors do not so state it is assumed that this study is based on level track and while this difference might be accounted for by an allowance made for a grade, at the same time if such is the case, the loadings on other tracks can hardly be assumed without making correction for the grade in opposite direction, which is not the case in the paper.

While the authors state in Table I that d-c locomotives are 5 per cent more efficient than a-c locomotives it does not appear how this allowance is made in connection with the freight and passenger trains given in Table V.

From a standpoint of practical railroad operation the writer does not feel that it is necessary to assume a d-c system flat regulated as was assumed in Table I. It seems that advantage might be taken of the ability of d-c equipment to operate without difficulty over a wide voltage range and the substation voltage be allowed to vary over a range of say 10 per cent which, with the allowance for an average line drop of 10 per cent, would enable a considerable interchange of power to take place between sections of the trolley. This is stated in the paper to be not as good as with the a-c systems, which statement however is somewhat open to question even without the arrangement described above. Under such a system and with proper design of passenger equipment, passenger trains may be held on approximately their scheduled speed throughout a wide range in voltage and freight trains allowed to slow down during times of maximum congestion. While such conditions are very difficult to figure and might be impossible to present in a paper such as this, at the same time they represent a practical solution of great value and one which should be given careful consideration.

Inasmuch as this paper deals primarily with substation spacing it would seem as though Table VI which gives considerable information on a number of electrifications should have included this item. It is interesting to compare the average spacing and the route miles per substation for a number of these actual electrifications which are given below and which show the

| Railroad | System | Approx. miles between substations average | Route miles per substation average |
|---|---|---|---|
| **Main Line Electrifications** | | | |
| Butte, Anaconda & Pacific | 2,400 v d-c | 24.5 | 18.7 |
| Chicago, Milwaukee, St. Paul & Pacific | | | |
| Rocky Mt. Division | 3,000 v d-c | 32.7 | 31.6 |
| Coast Division | 3,000 v d-c | 28.3 | 27.3 |
| Great Northern | 11,000 v a-c | 13.9 | 10.3 |
| Norfolk & Western | 11,000 v a-c | 8.3 | 7.0 |
| Virginian | 11,000 v a-c | 10.9 | 9.6 |
| New York, New Haven & Hartford (incl. NY W &. B) | 11,000 v a-c | 4.5 | 5.1 |
| **Suburban or Terminal Electrifications** | | | |
| Illinois Central | 1,500 v d-c | 5.4 | 5.4 |
| Delaware Lackawanna & Western | 3,000 v d-c | 11.9 | 13.6 |
| Cleveland Union Terminal | 3,000 v d-c | 10.7 | 8.5 |
| Reading | 11,000 v a-c | 6.7 | 6.3 |
| New York, New Haven & Hartford (inc. NY W & B) | 11,000 v a-c | 4.5 | 5 1 |

opposite trend from that which one would gather from the paper, so far as 3,000- d-c and 11,000-volt a-c substation spacings are concerned.

From a review of the preceding table it would appear that either there are a number of other factors involved in actual locations of substations, that are not brought out in this paper, or else the accumulation of the points mentioned in the discussion above is such as to cause different results to be obtained in practise from those illustrated in the paper.

On the Hudson side of our Electric Division we are handling 14 car multiple unit trains—18 car (Pullman) passenger train and 3,500 ton freight trains on four tracks with average substation spacing of 3.4 miles. The substation voltage varies from 700 to 625 volts direct current while the average voltage at the trains is approximately 575 volts. This is given as an illustration of what can be done with a d-c system using a more or less flexible voltage at the substations.

**P. L. McGee and E. L. Harder:** Space limitations prevented a more detailed explanation of the various tables and charts included in the paper and the additional data, supplied by Mr. MacLeod together with the following brief reply to Mr. MacLeod's and Mr. Hamilton's discussions may assist in a better understanding of the basic assumptions made in the paper.

Mr. D. R. MacLeod refers to the many economic factors which must be considered in railway electrification and assumes that the authors' representation of fleet movements refers only to dense traffic and further refers to the methods of laying out a system for normal loads with certain checking for abnormal conditions.

Our paper is concerned primarily with the technical requirements of power supply point spacing, substation spacing, and converting capacities at these points with any given unit load. It is the authors' belief that when these technical conditions are fully satisfied for any given voltage class and transmission system, that the economic problems are relatively simple and that most of the confusion today in considering railway distribution systems, is caused by attempting to adjust the technical requirements to suit some preconceived economical condition. The interpretation that a fleet movement of trains employs very dense traffic, is incorrect. In any analysis of railway loads traffic train charts are employed, showing the space-time relation of all trains over the period considered. This chart may represent light traffic or dense traffic as the occasion requires. Railroads, however, in common with other utilities that supply services, are built to accommodate demand at its peak and if the electrification distribution and transmission are to conform to this condition they should be laid out to accommodate some recognized maximum traffic condition. There can be no more satisfactory representation for this purpose than a train fleet that lends itself to a simple mathematical analysis, as shown by the various figures included in the paper. This analysis lends itself equally well to level track, rolling and grade profiles.

In view of the proposed extensive consolidation of railroads and the probable diversion of traffic to particular lines in order to obtain maximum economy in operation, it becomes doubly necessary to consider railway transmission and distribution systems in the light of the maximum traffic that can be accommodated. In the second part of the paper, Table V, it is shown that the installed substation capacity in kilowatts per main line single track mile, would vary for the 3,000-volt d-c system and 12,000-volt a-c system between the following limits for the various class loads assumed. Class A, 206 to 241; Class B, 337 to 266; Class C, 501 to 435. These installed substation capacities with their corresponding supply point transmission capacities, are a measure of a railroad's capacity to perform work at a given rate and are very important values from the point of view of the railway operator.

There are numerous factors, mostly economic or pertaining to operation, which must be considered in connection with the electrical limits given in the paper in order to determine the best substation spacings. However, with the particular limit emphasized by Mr. MacLeod the authors disagree. Breaker discrimination may limit the permissible station spacing with overcurrent operated relays or breaker trips. However, this limitation is removed by trolley high speed impedance relays. The need for reasonably frequent trolley sectionalizing and limitation of the magnitude of inductive effects are more important factors than breaker discrimination in fixing outer limits of substation spacing.

We cannot agree with Mr. MacLeod's last paragraph. When current is drawn from a trolley at one station, whether it be load or fault, some of it comes through the transformers at that station and some over the trolleys from the adjacent stations. The latter part is termed "through feed." If the same system is laid out with longer trolley sections and relatively more transformer capacity at each station the through feed will be reduced by both changes, or by either one alone.

Mr. Hamilton questions the current carrying capacity of the contact system shown for the 3,000-volt d-c system in Table II and refers to an article by Schurig and Frick on the heating of wires. The values shown in Table II and Fig. 6 curve *A*, were calculated from Luke's formula and check very closely with tests carried out by Woll and Gable and described in the *Electric Journal*, November 1926. These values also check very closely with Schurig and Frick for cable sizes up to 600,000 cir mils as shown in the *General Electric Review*, August 1931, Table I.

The current carrying capacity from the heating standpoint with any combination of wires in parallel, is controlled by the hottest wire, which in this instance, is the messenger wire. The messenger wire considered, has the following characteristics and heating limitations according to Luke and Frick:

| Wire diameter (inches) | Total cir mils | Equivalent copper conductivity cir mils | Amperes for 50 deg C rise | |
|---|---|---|---|---|
| | | | Luke | Frick |
| 1.02 | 792,000 | 586,000 | 765 | 837 |

The equivalent conductivity of the auxiliary wire and two bronze contact wires, is 443,600 cir mils. With the current limitations of the 586,000 cir mils equivalent copper messenger wire and 50 deg C rise, the total capacity for the system, according to the two authorities, is as follows:

| | |
|---|---|
| Luke | 1,340 amperes |
| Schurig and Frick | 1,450 amperes |

Most engineers would prefer to run at a somewhat lower temperatures than the 50 deg C rise, especially with a supporting messenger wire and the small differences obtained between the two authorities are of no real importance. Mr. Hamilton's value of 2,065 amperes was probably obtained by assuming a current density in the auxiliary and contact wires to obtain a 50 deg C rise in these wires. This would cause an altogether excessive temperature rise in the messenger wire.

In connection with the question of substation spacing and tying of contact systems together between stations, our paper has attempted to cover all likely conditions by giving in Fig. 8, permissible spacing on a single track mile basis and in Table V, a permissible spacing with two or four tracks paralleled midway between stations, both with and without a load on the second track. By selecting a combination of trains likely to pass between substations from curves in Fig. 8, any likely condition may be approximated. The desirability of more or less paralleling points between substations is largely a matter of personal opinion. With the normal spacing encountered in practise, there is very little improvement in the average voltage to a moving vehicle by paralleling at more than one point and simplicity in sectioning and selectivity require a minimum of paralleling points.

Mr. Hamilton presents a table showing the effect of paralleling tracks where substations are spaced 25 miles apart. It would be rather an exceptional railway that would electrify four tracks to accommodate a medium load on one track over a distance of 25 miles and examples such as this appear to have very little practical value.

Mr. Hamilton questions the large number of trains assumed in the local suburban service. The maximum local suburban service assumed consists of trains at 2.4 minute intervals, or 25 trains per hour over one track, giving a total of 37 trains in one and one-half hours, which although it represents heavy traffic, approximates the maximum encountered in certain of our suburban systems. The fact that the load was assumed to continue over one hour has little influence either on the spacing or capacity of substations. A three to six train fleet probably would dictate from a regulation standpoint the spacing of substations.

Since the power demand values given by the authors are at such variance with those tabulated by Mr. Hamilton, the complete computation of the power demand at substation trolley bus with the main line trains employed in Table V is given below. In the matter of locomotive and distribution efficiencies it was assumed that the d-c and a-c locomotives have an average overall efficiency of 85 per cent and 80 per cent respectively and that the contact distribution efficiency is 90 per cent for the d-c system and 95 per cent for the a-c system, giving an overall locomotive and contact line efficiency of 76.5 per cent for both systems. On this basis the average power demand for the two systems is obtained as follows:

FREIGHT TRAINS

| | Schedule speed 30 mph | | | Free running speed 40 mph |
|---|---|---|---|---|
| Car size tons | Trailing resistance per ton-lb | Locomotive resistance and acceleration allowance per trailing ton | Total resistance per trailing ton | Power demand kw at substation |
| 30 | 9.0 | 1.2 | 10.2 | 2,000 |
| 40 | 7.8 | 1.2 | 9.0 | 3,500 |
| 60 | 6.1 | 1.2 | 7.3 | 5,700 |

PASSENGER TRAINS

| | | | | Free running speed 70-75 mph | |
|---|---|---|---|---|---|
| Schedule speed 60 mph | | | | Heating and auxiliary power demand at sub/train | Total kw at substation |
| 75 | 8.75 | 3.25 | 12.0 | 520 | 2,400 |
| 75 | 8.75 | 3.25 | 12.0 | 760 | 3,600 |
| 80 | 8.35 | 3.25 | 11.6 | 1,000 | 4,600 |

The freight train resistances are taken from the *University of Illinois Bulletin 43* and the locomotive and passenger car resistances are taken from the *General Electric Review*, October 1926, pages 685 to 707.

An important item that often is overlooked in modern freight traffic studies, is the train speed, which in Table V is taken to average 30 mph. In the passenger service the amount of auxiliary power for heating in winter and air conditioning in summer, becomes quite an important item. In Table V, an average substation demand of 40 kw per passenger car was assumed for heating. Possibly the exclusion of these items accounts to a large extent for the extraordinary low values tabulated by Mr. Hamilton.

The paper is not concerned primarily with substation spacing, and as pointed out, spacing may be varied over a considerable range without affecting the required substation capacity.

Mr. Hamilton considers a shunt characteristic ideal with d-c converting machines. This always has been the authors' opinion but with this qualification, that the voltage practically be flat to full load rating of the machines. Opinions evidently vary on this point as the most recent 3,000-volt installation in this country was initially compounded. This has, however, been changed to a shunt characteristic. The authors cannot subscribe to the wide substation voltage fluctuations proposed by Mr. Hamilton. The most favorable assumption in considering a fleet movement passing a series of substations is a flat characteristic. Under such conditions there would be no advantage in lowering all substation voltages and it must not be overlooked that any transfer of power over long distances is uneconomical with low voltage systems. The high voltage a-c contact systems inherently lend themselves to economical transfer of power.

As suggested by Mr. Hamilton, it would of course be interesting to tabulate the substation spacing employed on various systems but this should be done by giving the spacing limits on any system rather than the average values tabulated by Mr. Hamilton. As an example: the Delaware, Lackawanna and Western Railroad spacing varies between 8.44 miles where traffic is at maximum to 15 miles where traffic is light. For a really illuminating comparison, however, the substation spacing employed on European and other continental systems should be included. In Germany, the alternating current track substations range from a spacing of 85 miles, whereas the 3,000-volt South African electrification has a minimum substation spacing of approximately 10 miles.

It is hoped that the authors' paper may in some respects assist in explaining the limitations imposed by the various spacings and installed capacities in substations.

Mr. Hamilton states that the average voltage on trains on the Hudson side of the New York Central electrification is 575 volts with a maximum substation voltage of 700. This represents an average voltage drop of approximately 18 per cent and although this may be quite satisfactory with terminal services and suburban trains where express service is not exacting, it is not a very economical arrangement and could hardly be recommended for main line train service where it would be necessary to derate locomotives to approximately 18 per cent.

# Simplified Speed Control for Single-Phase Locomotives

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**Synopsis.**—*Particular reference is made in this paper, to a recently developed, greatly simplified control system for high-voltage, single-phase locomotives, where the entire heavy and bulky switchgear is replaced by a simple high-voltage tap changer. A short description is also given of various other control systems which are today used on electric single-phase locomotives, and the strong and weak features of such systems are discussed. No reference is made to control systems for split-phase or motor-generator locomotives.*

## INTRODUCTION

WITH the introduction of electric propulsion of trains on main railway lines, it was soon realized that comparatively high voltages would be necessary to conduct economically the required energies to the moving vehicles. Late developments followed, with some exceptions, two distinctly different directions, namely; the high-voltage direct current and the high-voltage alternating current systems. With alternating current, the transformer presented a practical means to take high-voltage current, collected at the trolley by a locomotive, and convert this current to any desired working voltage, suitable for the traction motors, and the auxiliaries. The matter was not quite so simple in the case of the direct current locomotive, and in the economical d-c locomotive of today, the energy collected from the trolley wire must be utilized at the voltage collected from the wires, without going through any stage of transformation.

As a result of this, we recognize that the maximum operating voltage for d-c main-line electrifications is approximately 3,000 volts.

For a-c railway electrifications, the upper limit of the working voltage on the trolley system is in no way interconnected with the locomotive motors. A-c railway electrifications in late years have been executed mostly with 11,000 volts, 25 cycles per second, single-phase in the United States of America, and 15,000 volts, 16 2/3 cycles per second in Europe.

## SPEED CONTROL OF HIGH-VOLTAGE SINGLE-PHASE LOCOMOTIVES

*A. General.* The electrical equipment of a commutator-motor locomotive, consists usually of the following main parts:

a. The current collector.
b. The transformer.
c. The voltage regulating apparatus or power switchgear.
d. The traction motors.
e. The auxiliary and control apparatus.

The purpose of the voltage regulating apparatus is to supply the motors with selectively predetermined voltages, and in that way to regulate the speed of the locomotive. There is no reference made in this paper to the various motor combinations that are possible, excepting in cases where the particular connection has a deciding influence on the speed-regulating apparatus.

Several systems of power control apparatus are already developed, which permit the varying of the voltage at the terminals of the motors. It is extremely important that the power flow to the motors be not interrupted during the transition from one transformer tap to the next one. Such an interruption of power flow between steps is destructive to the motors, the gearing, if such is used, and to the mechanical parts of the locomotives as a whole.

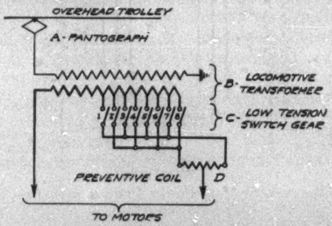

FIG. 1—DIAGRAM OF MAIN POWER CIRCUIT WITH ONE PREVENTIVE COIL

*B. Unit Switch Control System.* Several methods have been used to accomplish the transition between transformer taps, without interrupting the power flow to the locomotive motors.

A few of the more usual combinations are shown in Figs. 1, 2, 3.

Fig. 1, shows a schematic arrangement of a control system with a certain number of switches, 1-8, utilizing a preventive coil *D*. These switches must be closed in a certain sequence to prevent short circuits between transformer taps of different potentials. The preventive coil *D*, is provided to insure a transfer from one tap to the next one, without interrupting the flow of power to the traction motors. It also permits that two switches of different potentials can be closed without producing an

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unduly high short-circuit current in the transformer section lying between these switches. The arrangement shown in Fig. 1, is quite often used abroad. Fig. 2 shows a system whereby triple preventive coils are introduced into the circuit. A control arrangement which is quite generally employed in this country is represented by Fig. 3. Three preventive coils are utilized in this circuit. Fig. 4 gives the sequence of switches for the control scheme shown in Fig. 3.

The limitation of design requires that the voltage of single-phase commutator motors, to obtain good commutation, be relatively low. Heavy currents, therefore, have to be handled by the switches if large size motors are involved. Furthermore, with 25 cycles per second, lower voltages must be applied at the motor terminals than with 16 2/3 cycles, therefore, higher currents must be handled by the switches in case of a 25 cycle locomotive, than in the case of 16 2/3 cycles. The following data clearly demonstrates the above statement.

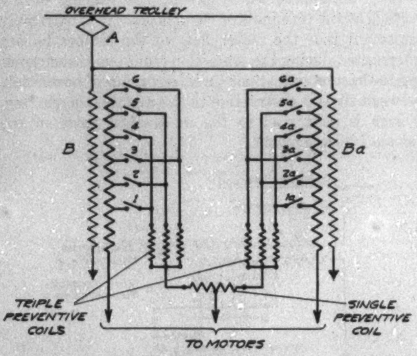


FIG. 2—DIAGRAM OF MAIN POWER CIRCUIT WITH TWO TRIPLE PREVENTIVE COILS

A single-phase commutator motor of approximately 625 hp, one hour rating, designed for 25 cycles per second operation and at a terminal voltage of about 285 volts, consumes a current of approximately 2,000 amperes. This same motor, built for 16 2/3 cycles, could be designed for a voltage of approximately 400 volts. Its current consequently would drop to about 1,425 amperes. Assuming that a locomotive is equipped with four such motors, all of which are connected in parallel, the total one hour current of these four motors would be 8,000 amperes, and the maximum starting current approximately 14,000 amperes. Therefore, in the case of an arrangement as in Fig. 1, the one-hour current that is to be handled by each switch is 4,000 amperes approximately, and for the arrangement shown in Fig. 3, only 8,000/4 or about 2,000 amperes.

There are several reasons why reactance coils are introduced in the main motor circuit.

a. They are necessary to secure a relatively constant power flow to the traction motors during the transition period.

b. They permit the employment of power control switches of smaller current carrying capacity than that corresponding to the total motor current.

c. They permit reduction in the number of high-current terminals on the transformer.

Most a-c locomotive control systems, however, using preventive coils during the transition period, show one very undesirable feature.

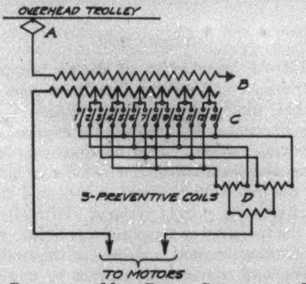
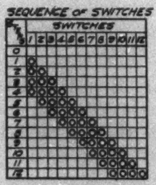


FIG. 3—DIAGRAM OF MAIN POWER CIRCUIT WITH THREE PREVENTIVE COILS

Upon studying any one of the previously mentioned wiring diagrams, we find the following conditions, which are characteristic to all of them.

Part $D$ of Fig. 5, represents a section of the low-voltage winding of a locomotive transformer. On each running step two switches will be closed. Assuming the switches 1 and 2 are closed, the motor current $I_o$ is composed of $I_o/2$ amperes flowing from transformer tap $D_1$, over switch 1 through leg $A_1-C_1$ of the preventive coil. The other $I_o/2$ amperes, flow from transformer tap $D_2$ over switch 2 through the leg $B_1-C_1$ of the preventive coil. At the point $C_1$, the two currents join to become $I_0$. The potential of point $C_1$ is just half-way between the two taps $D_1$ and $D_2$. However, with an arrangement as shown in Fig. 5, the ampere turns of the two windings $A_1-C_1$ and $B_1-C_1$ compensate each other. In order to reach the next higher running step,


SEQUENCE OF SWITCHES

| STEPS | SWITCHES | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 0 | | | | | | | | | | | | |
| 1 | ○ | | | | | | | | | | | |
| 2 | ○ | ○ | | | | | | | | | | |
| 3 | ○ | ○ | ○ | | | | | | | | | |
| 4 | ○ | ○ | ○ | ○ | | | | | | | | |
| 5 | | ○ | ○ | ○ | ○ | | | | | | | |
| 6 | | | ○ | ○ | ○ | ○ | | | | | | |
| 7 | | | | ○ | ○ | ○ | ○ | | | | | |
| 8 | | | | | ○ | ○ | ○ | ○ | | | | |
| 9 | | | | | | ○ | ○ | ○ | ○ | | | |
| 10 | | | | | | | ○ | ○ | ○ | ○ | | |
| 11 | | | | | | | | ○ | ○ | ○ | ○ | |
| 12 | | | | | | | | | ○ | ○ | ○ | ○ |

FIG. 4—SEQUENCE DIAGRAM OF SWITCHES FOR FIG. 3

switch 1 must open before switch 3 closes, as otherwise the respective portion of the transformer would be short-circuited.

It is evident that for a moment, after switch 1 has opened, but before 3 is closed, the entire motor current $J_o$ flows from transformer tap $D_2$ over switch 2 through the winding $B_1-C_1$ of the preventive coil. The winding $B_1-C_1$ now carries almost twice the current that it did before and since winding $A_1-C_1$ has no current at all at this moment, the ampere turns of winding $B_1-C_1$ are now also about twice of what they were before and are not compensated any more with the result that winding $B_1-C_1$ now acts as a highly saturated reactance coil. The entire motor current $J_o$, which now flows in the circuit is, however, somewhat lower than what it was before, on account of the inductive voltage drop of the now uncompensated preventive coil part $B_1-C_1$. An instant later switch 3 closes, hereby again establishing the original balanced conditions in the preventive coil. The current $J_o$ that now flows in the circuit is higher than that before the transition was made, because the system through switches 2 and 3 is now connected to transformer taps of higher voltage. The sudden changes in the magnetic conditions of the preventive coil are a source of voltage surges which can be detrimental to the apparatus connected to it. The above mentioned variations of the motor current are felt in very undesirable fluctuations of the torque of the motor. These fluctuations can have a decidedly bad influence during the starting period of the locomotive when the accelerating forces are close to the adhesive limits of the locomotive.

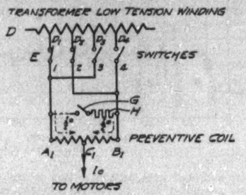


Fig. 5—Diagram of Unit Switch and Preventive Coil Control System

It is possible to minimize the voltage surges during the transition period somewhat by introducing a resistance $H$ across the terminals $A_1-B_1$ of the preventive coil. In order to minimize the losses in this resistance $H$, it is advisable to provide a switch $G$, as shown in Fig. 5. This switch is closed during the transition only.

*C. Control System with Bridging Resistances.* For many years efforts have been made to eliminate the above mentioned undesirable effects and to produce a control system which would give smooth acceleration.

In the writer's opinion, this can be obtained when the transition from one tap to the next one is accomplished with a bridging resistance. This can be done in two ways:

1. Tap-changing by means of a bridging resistance takes place on the low-tension side of the locomotive transformer.
2. Tap-changing by means of a bridging resistance takes place on the high-tension side of the locomotive transformer.

*D. Low-Tension Tapping Switch Control System.* A satisfactory low-voltage power control system of single-phase locomotives, one that assures smooth transition from one transformer tap to the next one, is illustrated in principle in Fig. 6. It is used to a very great extent abroad where more than 300 single-phase locomotives are equipped with it. In this system the number of taps on the transformer are equal to the number of running steps of the locomotive. Each transformer tap is connected to a block contact, $X_1-X_n$ of the tap-changing apparatus.

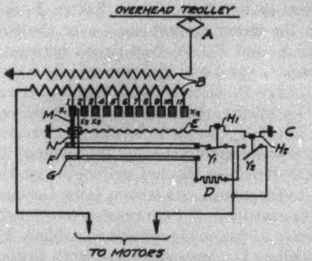


Fig. 6—Diagram of Main Power Circuit with Low-Tension Tapping Switch

Two brushes $M$ and $N$, (one main and one auxiliary brush) are arranged in such a way that they can be moved along the block contacts by means of a screw $E$. The main brush $M$ is constantly in contact with busbar $F$, whereas the auxiliary brush $N$ is always connected with busbar $G$. The operating screw $E$ is usually motor driven, but manual operation is also easily possible. Busbar $F$ connects with switch $Y_1$; busbar $G$ through the damping resistance $D$, connects with switch $Y_2$. The operation of this tap-changer is as follows:

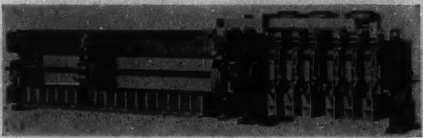


Fig. 7—Tapping Switch with Six Arcing Switches for Three 800-Hp Single-Phase Motors

Assuming that brush $M$ is on block contact $X_1$ (running position 1, for instance), when switch $Y_1$ on account of its connection with crank shaft $H_1$ is closed, and the current flows directly to the motors. The auxiliary brush $N$ is now between block contacts $X_1$ and $X_2$, so that no current can flow through it. Furthermore, switch $Y_2$ being connected with crank $H_2$, which is opposedly located to $H_1$, is open. To make the transition from tap 1 to tap 2, the screw is rotated in such a direction that both brushes $M$ and $N$ move towards block contact $X_2$. The auxiliary brush $N$ reaches block $X_2$, before switch $Y_2$ is closed. Switch $Y_2$ now closes so that the motor current flows over the two arcing switches $Y_1$ and $Y_2$. A short circuit between the two transformer taps 1 and 2, is prevented on account of the resistance $D$, which is in the circuit of the auxiliary switch $Y_2$. Before the main brush $M$, however, leaves block contact $X_1$, switch $Y_1$ breaks that circuit and the current flows now only through the auxiliary brush $N$, busbar $G$, resistance $D$, and switch $Y_2$ (which is now closed) to the motor. An instant later, the main brush $M$ leaves contact $X_1$. Both brushes move on until the main brush $M$ has made contact with block $X_2$. Now arcing switch $Y_1$ closes again and both brushes carry the motor current for one moment. An instant later, arcing switch $Y_2$ is opened, so that no current is broken when the auxiliary brush $N$ leaves block $X_2$. The same cycle as illustrated is repeated whenever a change to another transformer tap is performed. With this arrangement, it is, therefore, possible to accomplish tap changing under load, without any current interruptions, at the brushes $M$ and $N$. All arcing is done by the arcing switches $Y_1$ and $Y_2$. The number of such arcing switches naturally depends on the current capacity and number of the main motors. Fig. 7 shows such a tap-changer having six arcing switches built for the control of three 800-hp single-phase motors. Fig. 8 shows a similar tap-changer built for the operation of two 1,250-hp single-phase twin motors having four arcing switches. As can be seen from Figs. 6, 7 and 8, the number of current-breaking switches is greatly reduced when compared with any other control system. For quick power interruption at any operating step, we recommend the insertion of an electrically or pneumatically operated switch into each motor circuit.

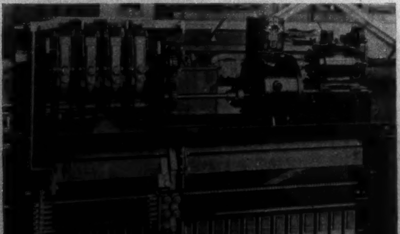


FIG. 8—TAPPING SWITCH WITH FOUR ARCING SWITCHES FOR TWO 1,250-HP SINGLE-PHASE MOTORS

The advantages of this control system, however, are quite numerous. From an operating standpoint, it has been experienced that a locomotive equipped with such a control system operates exceedingly smooth, due to the absence of any undesirable current variations during the transition periods, and particularly during the period of acceleration, no jerking or shocks of any kind can be felt. The result is that locomotives with this type of control have considerably less tendency to slip the wheels. The tapping switch control system, furthermore, is lighter and requires less space than a contactor control system, and the maintenance cost of it is lower. The tapping switch, furthermore, can be built together with the locomotive transformer in such a way that very short copper connections between transformer and control apparatus are required.

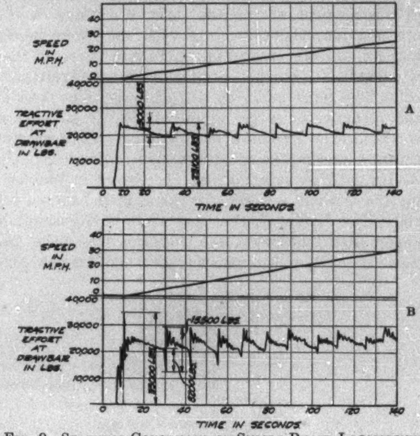


FIG. 9—STARTING CONDITIONS OF SINGLE-PHASE LOCOMOTIVES

A. Locomotive equipped with tapping switch control system

B. Locomotive equipped with preventive coils and unit switch control system

That the transition of control steps of a locomotive with tapping switch control usually are exceptionally smooth, is clearly shown in Fig. 9, which shows the starting diagrams of two single-phase locomotives which were built for the same service requirements. Both diagrams were recorded by the indicator of a dynamometer car on the same day and with the same train (weight 520 tons). The diagram for locomotive $A$ shows conditions for a locomotive with tapping switch control, whereas, the curves for locomotive $B$ represent those of a locomotive with preventive coils and unit switch control system. The bottom curve shows the tractive efforts measured at the draw bars of the locomotives, whereas the top line indicates the speed of the train. Upon comparing the two characteristics, it will be noted that the tractive effort variations during each transition for locomotive *B*, reach approximately 15,500 lb: for locomotive *A*, they amount to about 5,000 lb, that is, are reduced to less than one third of the above value. Locomotive *B* incidentally was accelerated somewhat faster as is indicated by the shorter time that was required to reach a certain train speed. A reduction of the accelerating rate of locomotive *B* will not eliminate the oscillations shown in the diagrams, although they might be reduced somewhat in their magnitude.

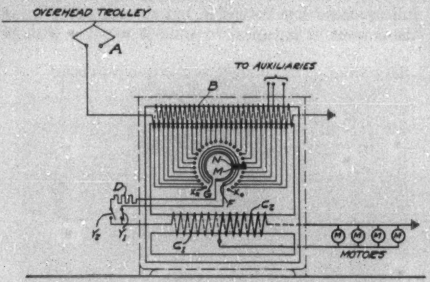


Fig. 10—Diagram of Main Power Circuit of Single-Phase Locomotive with High-Tension Tapping Switch

It would, however, be unjust to ascribe the above mentioned conditions entirely to the electrical control system used in each locomotive. It is not only the control system that is responsible, for what is being measured at the drawbar of a locomotive, but also the kind of mechanical transmission that is interposed between driving motor and locomotive wheels, and the kind of spring arrangement of the couplers. In the case of the above mentioned comparisons, each motor of locomotive *A* was equipped with a flexible pinion, a solid gear and a Brown Boveri individual axle drive (Buchli gear). The only flexible member in this entire drive system is the spring pinion. The *BBC* individual axle drive does not permit any angular displacement between the driving and driven parts. Locomotive *B* was equipped with solid pinions and gears, but as the flexible medium between the gear and the driving wheel, a spring quill drive was used. The flexibility of this quill drive is considerably greater than that of the flexible pinion of locomotive *A*, with the result that certain motor torque variations created by the control system are magnified on account of possible angular oscillations of the motor armatures with regard to the axles.

The above discussion does not particularly mention the ways in which the various switches in each control system are controlled. There are numerous ways to accomplish this. Most unit switch control systems use either electropneumatically or electromagnetically operated switches. Other systems utilize a cam shaft, which when rotating, closes the switches in a predetermined sequence. In a control system as shown in Fig. 6, representing a tapping switch arrangement, no special interlocks are necessary either, as the crank shaft and the screw automatically synchronize the arcing switches and the moving brush contacts.

We have previously mentioned that the current capacities which have to be handled on the secondary side of a high-powered single-phase locomotive, reach quite high values. This means that all apparatus inserted in that circuit, such as unit switches, tapping switches, preventive coils, reversers and all copper interconnections between the various apparatus, must be designed to carry these currents.

*E. High-Voltage Tapping Switch Control System.* A new control system, which disposes of all the compli-

Fig. 11—Single-Phase Locomotive with High-Tension Control of 3,750 Hp, 1 Hour Rating with Side Walls Removed

cated and heavy low-tension apparatus of single-phase locomotives, has recently been developed. It has been put into successful operation on some large locomotives on the Swiss Federal Railways. With this system, the motors with their reversers are directly connected to the low-tension terminals of the transformer. This is accomplished by shifting the voltage regulation to the high-tension side of the transformer. Fig. 10 shows the principal diagram of the high-tension control system.

The high-tension current collected from the overhead wire, flows into the high-tension transformer coil *B*. This coil is equipped with a certain number of taps $X_0 - X_n$. When starting the locomotive, the tap changing elements gradually move from tap $X_0$ towards the tap $X_n$. At this last tap the coils $C_1 - C_2$ obtain full potential, and, therefore, also the motors which are connected to winding $C_2$. Switching from one tap to the other one is accomplished in the same manner as with the tapchanger shown in Fig. 6. The same smooth operating characteristics are, therefore, obtained as with locomotive *A* of Fig. 9. The principal difference, however, in addition to extreme simplicity is, that the high-tension tapchanger carries comparatively small currents, as is indicated by the following.

A single-phase locomotive for operation on an 11,000-volt, 25-cycle, a-c system having four 625-hp motors, two of which are permanently connected in series, and the two groups in parallel, draws approximately 6,500 to 7,000 amperes during the start, which current must be carried by all apparatus in that circuit. If the same locomotive is equipped with high-tension control, it is evident that during starting, when the low-voltage control system carries the heaviest currents, the high-tension control carries only a comparatively small current. In the case of the above mentioned locomotive, and for 11,000 volts on the high-voltage side, approximately 350 amperes.

The entire tap changing under load operation, is in this case accomplished by the tap changing unit which operates sparklessly and two sparking switches. Since this tap-changer has to handle any voltage up to the full overhead line potential, but since it never breaks the current, it is logical to build it together with the main transformer and to submerge it in oil in order to obtain better insulation. This arrangement gives very small dimensions. The oil insulation, furthermore, provides excellent automatic lubrication and good cooling of the apparatus. It is, of course, also possible to connect the high-tension tap-changer to an air-blast transformer. In that case the advantage, namely; that of an unusually large saving of space encountered with the oil transformer and tap-changer unit will be greatly minimized because the leads connecting the high-tension transformer winding with the tap-changer, and spacing of taps within this apparatus itself, must be spaced considerably wider on account of being in air.

A locomotive with side walls removed and equipped with such a high-tension control system, is shown in

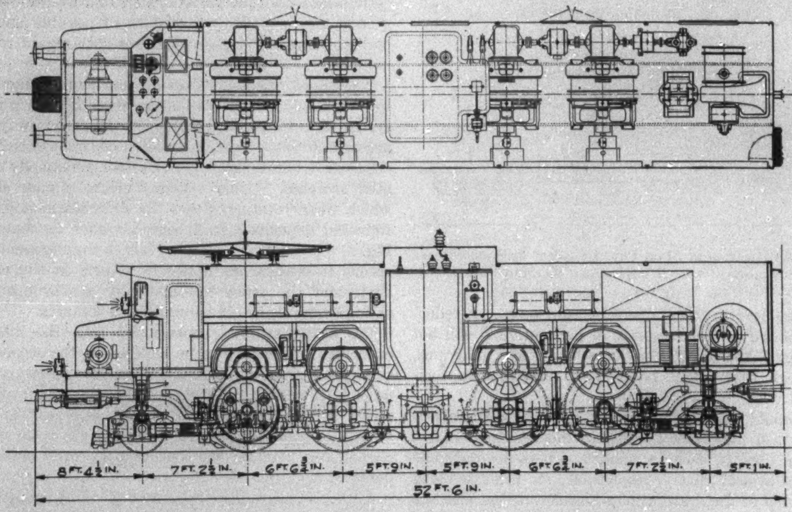


Fig. 12—Arrangement of Apparatus of 3,750-Hp Single-Phase Locomotive

Single-phase a-c express locomotive; type: $1B_0\ 1B_01$ with high-tension switchgear. Tractive effort—one hour = 37,700 lb at 38.55 mph, one hour rating of motors: 3,750 hp

Fig. 11. Fig. 12 gives the general arrangement of apparatus for the same locomotive. Fig. 11 shows particularly how accessible the motors become, due to the absence of a great many low-tension apparatus, which in other locomotives fills the entire cab.

The oil transformer built together with the high-tension controller is located in the middle of the locomotive as one unit. At the left end of the cab, the oil cooling unit can be seen. The control apparatus that are located opposite the railway motors are necessary because this particular locomotive is equipped for regenerative braking. Fig. 13 illustrates the oil transformer mounted over the middle idling axle and plainly shows how the tap-changer is attached directly to the transformer housing. The two contactors $X_1$ and $Y_2$ of Fig. 10, are outside of the transformer tank, arranged in such a way that by means of a cam shaft they are always synchronized with the tap-changing unit so that no current is broken within the oil tank. We have thus, a control system that utilizes only two arcing switches for the entire main power control range of the locomotive. It is expected that the erection and maintenance cost of a locomotive will appreciably be reduced with this new control system.

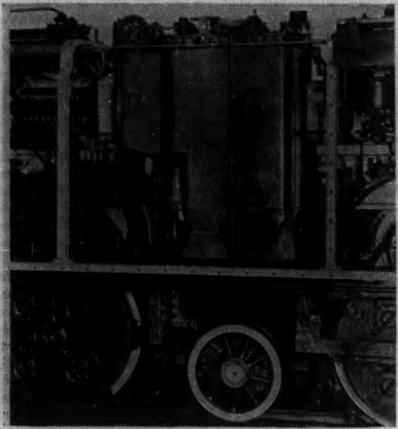


FIG. 13—ARRANGEMENT OF TRANSFORMER IN MIDDLE OF LOCOMOTIVE

Besides simplifying the arrangement and improving the accessibility of the main motors within a locomotive cab, this new control system also permits a reduction of the weight of the electrical equipment. This is shown in the following indicated weight comparison, which is for an 11,000-volt, 25-cycle a-c locomotive, equipped either with the high-tension tapping switch control or with a unit switch control system. No weights are indicated for apparatus that is common for both control systems, but only those that differentiate each locomotive from the other. The locomotive in question is equipped with four 850-hp single-phase railway motors.

| | |
|---|---|
| *A. Locomotive with Unit Switch Control System* | |
| Air blast main transformer—3,500 kva | 25,500 lb |
| Three preventive coils | 4,500 lb |
| Approximately 22 contactors, including mounting frames | 5,000 lb |
| Blower group for transformer and preventive coils | 2,800 lb |
| Copper connectors between transformer, preventive coils and switch groups | 1,500 lb |
| Total | 39,300 lb |
| *B. Locomotive with High-Tension Control System* | |
| Oil cooled main transformer—3,500 kva (including oil) | 27,000 lb |
| High-tension tapping switch, including pilot motor drive | 1,300 lb |
| Oil cooler complete and oil pump | 4,800 lb |
| Oil in pipes and cooling unit | 600 lb |
| Total | 33,700 lb |

| | |
|---|---|
| Locomotive *A*—total | 39,300 lb |
| Locomotive *B*—Total | 33,700 lb |
| Saving in weight approximately | 5,600 lb (2.800 tons) |

## Discussion

**C. J. Axtell:** One of the points of the paper upon which the writer comments is in regard to the acceleration charts (Fig. 9). Two differences exist in these two locomotives, *viz.*, locomotive *A* has a resistance type of transition and also a type of mechanical drive between the motor and the driver which offers but a very small amount of flexibility. Locomotive *B* has a preventive coil type of transition in changing from one transformer tap to another and also a spring quill drive giving much more flexibility between the armature shaft and driver than locomotive *A*.

In the accelerating chart of locomotive *B*, it will be observed that the draw-bar pull when power was applied to the motors on the first point had the greatest oscillation shown at any point on the curve. However, on this point the transient conditions described as taking place when transferring from one tap to another are not present, consequently we must look to something other than the control as the cause of this oscillation. On the succeeding notches the curves show the oscillations prolonged for from 10 to 15 seconds duration. Any electrical transient set up would be over entirely in a few cycles, consequently this too points to causes other than the type of control as contributing the principal influence in setting up these oscillations in tractive effort. Tests that have been made show that the flexibility of the drive can produce exactly the results shown in the charts.

In the scheme of control involving high-tension switching as shown in Fig. 10, the comparison of weights of the transformers is shown as 25,500 pounds for the single air-cooled transformer and 27,000 pounds for the oil-cooled transformer used with high-tension switching. Since this latter system involves the use of two-autotransformers with the magnetic structure so arranged as to give interlinkage of flux, it would seem that such a small difference in weight of the two transformers largely is accounted for in the designs due to different methods of cooling rather than due to the different methods of switching.

**C. Kerr, Jr. and F. B. Powers:** Fig. 9 shows the notching for two types of locomotives, one with tap changes and one with preventive coils. This is not a fair comparison. The locomotive with preventive coils was accelerated at a 30 per cent faster rate, so that the increment naturally will be greater. Secondly, the same figure, an increment of 15,500 lb is shown with the preventive coil. With modern designs of preventive coils with suitable air gaps, increments as shown by Mr. Giger are not encountered, and to compare the two systems justly, properly designed preventive coils should have been used.

A tap changing control using a bridging resistor must provide sufficient capacity in the resistor to handle the main motor current continuously. Otherwise, a failure of the control which leaves the resistor in the circuit will overload the resistor.

The weights given by Mr. Giger in the last paragraph of his paper do not compare favorably with present American practise. The figures given by Mr. Giger and present practise are compared below:

| | Mr. Giger's weights | Present American practise |
|---|---|---|
| Air blast transformer—3,550 kva | 25,500 lb | 22,000 lb |
| Three preventive coils | 4,500 lb | 2,550 lb |
| 22 contactors, including supports | 5,000 lb | 2,450 lb |
| Blower group | 2,800 lb | 1,000 lb |
| Copper connections | 1,500 lb | 2,700 lb |
| | 39,300 lb | 30,700 lb |

Mr. Giger gives a weight of 33,700 lb for the high-tension tap changing equipment comparable to the above weight of 39,300 lb. As this locomotive has been built, we presume this weight to be correct. Therefore, instead of a saving of 5,600 lb over the system now used, as indicated by Mr. Giger, the high-tension tap changing equipment would weigh 3,000 lb more, provided the air blast equipment and switches were made comparable to the latest locomotives placed in service in this country.

The limitations of the preventive coil notching scheme have been appreciated for some years. Simultaneously, the advantages of the tap changing type of control have been fully appreciated. In this discussion we have attempted to give a comparison between the two systems, without condemning either, but we feel that the tap changing system, as at present developed, is not the final answer to the ideal control.

**Walter H. Smith:** The two curves illustrated in Fig. 9 are somewhat of a mystery, since the writer never has been able to record with the oscillograph, armature current surges with a properly designed preventive coil while switching, sufficient to give as great tractive effort variations as indicated here. It is granted that it is possible to more nearly realize the ideal condition outlined in Mr. Moore's paper[1] with resistors. However, with properly designed preventive coils applied at the same place in the circuit as resistors, their performance will so closely duplicate the resistor that it is doubtful whether an operator would know the difference. It might also be pointed out that experience in America with resistors in alternating-current traction circuits has been unsatisfactory.

It will be seen that the two locomotives, *A* and *B*, although designed for the same scheduled speeds and service are different in that locomotive *A* has about 30 per cent less accelerating rate than *B*. Locomotive *A* uses resistors for changing taps on the high side of the transformer while *B* uses preventive coils on the low side. It should be noted further that the drives that are furnished by two independent manufacturers, are different, which may to a large extent, account for some of the differences in the dynamometer record. In the writer's opinion if properly designed preventive coils were substituted in place of the resistors on locomotive *A* and the two performance curves compared, an entirely different picture would be presented.

In regard to the high-tension tapping switch system of control outlined in Fig. 10, the writer believes that with the present knowledge of insulating materials, the art has reached a stage where this system has possibilities. High-tension tapping was advocated by the writer for multiple unit cars as far back as 1923 because it was believed at that time that it could be built lighter, more simple, and was best suited for that service.

It is pleasing to see that it has been revived again in America and it is hoped that in the near future we shall be able to see a motor car or locomotive of this type in service. With the advent of the high-speed transformer station trolley breaker all previous objections to this system of control probably will be eliminated. Mr. Giger's paper has laid considerable stress on its great simplicity and states that only two contactors are required. Experience in America has shown that a single contactor cannot be relied on always to open the circuit. For this reason additional contactors will be required. A circuit leading to traction motors should be interrupted in at least two places when cutting off power.

In this diagram, parallel connections for all motors are indicated. This is the greatest assurance that we have against slipping traction wheels and the resulting damage to motors that may occur. Mr. Giger has said very little about this and the writer would like him to tell us more about this point and also the practise in Europe as regards parallel motors.

**W. A. Giger:** Mr. C. J. Axtell is not quite correct in his assumption that the oscillation on the first point is the greatest one. The maximum tractive effort peak of 33,000 lb was reached on the third step. The first three operating steps are very close together and show peak values of approximately 15,000, 23,000 and 33,000 lb, respectively. Upon close investigation it can, be seen however, that at each transfer the current first dropped considerably before it jumped to the value corresponding to the higher voltage tap. No oscillations are shown for the first two steps, because the engineer advanced his master controller quite fast up to the third position, where he was forced to wait because the maximum tractive effort was reached. If a time delay had been made at the first and second steps, the same general characteristic of lower magnitude would have been registered, as is shown for the higher taps. The oscillations are, as correctly stated by Mr. Axtell, taking place in the mechanical parts of the drive system, but the initiator for them is found in the current and consequently torque variation of the motor armature during the transfer. By employing a somewhat different mechanical transmission between motors and locomotive wheels, probably one that contains some damping elements, the oscillations could be checked very readily and would disappear after a very few cycles. As Mr. Axtell furthermore correctly states, the comparatively small difference in the weight of the standard low voltage control transformer and the high voltage control transformer actually is due to the utilization of oil cooling for the latter. Regardless of this, however, remains the fact that the high tension control apparatus weighs only 1,300 lb as against about 9,500 lb for contactors and preventive coils, in case of the low voltage control.

Referring to the discussion by Messrs. C. Kerr, Jr. and F. B. Powers, the author wishes to point out that the two locomotives, the starting conditions of which are shown in Fig. 9, were built by different firms *for the same service conditions*. It certainly cannot be said that comparison of them is not fair, because one type of locomotive was equipped with a substantially better system of control. Both firms were at freedom to use whatever they felt would comply with the specifications. The fact that one locomotive was accelerated faster during the test does in no way indicate that the oscillation characteristics to locomotive *B* would disappear if the same acceleration would be used. However, since no other diagrams were available, the ones at hand had to be used and it was brought out clearly in the paper that a reduction of the accelerating rate would reduce the swings in their magnitude, but would not eliminate them. The author has been able to establish for himself on a number of the latest a-c railway vehicles in this country the fact that even modern designs of preventive coils will not give such a smooth start (for the same number of operating steps) as the resistance bridging method equiped with preventive coils.

Contrary to the indication made by Messrs. Kerr and Powers, it is not necessary to provide bridging resistors capable to carry the entire main motor current continuously. About 360 locomotives and motor cars are in satisfactory operation with such resistors, yet not a single one has been designed for carrying the motor current continuously.

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[1] See page 356.

The weights for parts of modern single phase locomotives, as indicated by Messrs. Kerr and Powers are quite interesting if compared with those given by the author. However, we do not believe that they are on a comparative basis. Particularly referring to the weight of 22 contactors, we hardly believe that the weight of the mounting frames is included in the 2,450 lb, but this weight was included in our case. It hardly seems possible to design a switch of the required capacity, including mounting structures with a weight of only about 110 lb, unless a system of electrically connecting the motors is assumed, to which we would not agree. The blower group as indicated by Messrs. Kerr and Powers is to have a weight of 1,000 lb. It would be quite interesting, however, to know what rating has been assumed for this blower group. Our estimates, which are also based on present American practise indicate a weight of the blower motor alone of about 1,200 lb. This does not include any starting equipment, such as reactors, etc., nor the blower wheel and housing. It must, however, be added that the transformer weight of 27,000 lb, as given for the high tension control system by the author, contains approximately 4,000 lb of oil, so that the actual weight of the apparatus is only 29,700 lb. If the weight indications of Messrs. Kerr and Powers are based on the same motor combinations and the same ratings per locomotive, then it can be shown that the high tension control still is lower in weight, than any low voltage control system. At this point refer to the weight of the locomotive shown in Figs. 11 and 12 of the paper. The transformer, including control and connections between transformer and control apparatus, weighs approximately 36,000 lb, as executed with the high tension control, whereas if built with the low tension control with low voltage tap changer, (which itself is already lighter than a contactor control system) it would have had a weight of about 41,000 lb or a difference in favor of the high tension control of about 5,000 lb.

With regard to the discussion of Mr. W. H. Smith and to the high tension control, the writer wishes to state that it is possible easily to provide a contactor for each motor or motor group on the low voltage side, in order to have a switching element that will take care of overloads or interruptions. Such contactors have been proposed already in a great number of cars, in order not to be dependent entirely on the two arcing switches which take care of the tap changing operation.

With regard to the parallel connection of the driving motors in single phase locomotives, the writer wishes to point out that this arrangement is used almost exclusively in Europe. Motors are connected in series only when they are connected mechanically together, such as is the case with twin motors working on the same gear, or motors working on different driving axles, but connected by side rods.

# The Professional Development of the Engineer

## BY R. I. REES[1]

Non-member

IN considering the objectives of education, there has been much confusion in the definition of terms. For many years past there has been heated discussion concerning the relative values of general and specialized education and also between culture and technology. Educational psychology, in its study of the basic fundamentals of learning, has made evident that there is no distinction between general and specialized education. In fact, there is no such thing as general education—all learning is a series of specializations. Nothing can be learned without giving undivided attention at any given time to a specific subject.

The child, from the day of his birth, focuses his attention upon a series of accomplishments which seem most important to him in getting along in the world. Impatient with his slow progress in crawling upon all fours, he determines to imitate his elders and learn to walk on his own two feet. He concentrates his whole effort upon this one objective and masters it. As a next step, finding difficulty in making his wants known through cries, smiles, and wriggles, he determines to learn to talk, and this effort becomes his focus of concentration.

Using these simple but most difficult achievements during our childhood simply as illustrations of distinct specializations in the learning process, do we not realize as individuals, that our whole progress of development through life is made up of ascending series of specializations or focuses of concentration? At the period of life in which we find ourselves today, the major focus of our concentration is on our job, with minor concentrations demanded of us by our environment. But let us bear in mind that when our attention is given to any particular subject, we are at that moment specializing. So let us have done with specious argument concerning general and specialized education. Our professional development depends upon the wisdom with which we plan a sequence of concentrations on subjects and things to be done, which will promote the highest degree of progress toward the objectives of our careers.

Just a word concerning the argument demanding that there be distinction between cultural and technological education. It seems to the writer that Professor Whitehead of Harvard has done away with this argument in the development of his educational philosophy. He divides all culture into three parts—the literary culture, the scientific culture, and the technical culture. The literary culture has to do with the mastery of language, a knowledge of history, some social science, and philosophy. The importance of the scientific culture is that it evokes logical thought involving the inductive and deductive methods. The two latter he picturesquely describes as the logic of discovery and the logic of the discovered. Through such a discipline the laws of nature are evolved. Technical culture develops the power to apply the principles of science to productive effort. It is the growth of manual and intellectual skill. He makes the point that no one of these cultures is complete in itself, but must be strengthened by something from the other two. When developed into a curriculum, it becomes a question of emphasis. Is it not implicit in this argument that engineering includes two of the basic cultures, and, in the present liberalization of its curricula, embraces to a considerable degree the literary culture also. In meeting the demands of our modern civilization, engineers may take satisfaction in knowing that their culture, more fully than any other, satisfies the fundamental demands of modern society. Apology is here offered for this very meager treatment of certain elements in educational psychology and philosophy which seem of importance to the engineer.

Particularly in the light of the great improvements which have been made during recent years in engineering education, it is safe to assume that the fundamental concentrations involved have formed sure foundations for progress in the engineering profession. But what of post-college professional development?

It is clearly realized that graduation from an engineering school does not, in and by itself, make a professional engineer. Numbers of years of experience and further intellectual development are needed before full recognition of professional status can be awarded. Progress toward full professional recognition depends almost exclusively upon the ambitious effort of the individual, realizing that education is a lifelong effort, and ends only when ambition ceases. Al through his undergraduate years, the student has received intimate guidance from the faculty, and has not had the responsibility, after selecting his curriculum, of planning his own development. After graduation, the responsibility rests with him to plan his future development. Of course, as has been said before, his plan of development must grow out of the demands laid upon him by his first job. Experience in the practice of engineering contributes most to professional development, but constant thought is needed coming out of the impacts of his experience, indicating the sequence of concentrations which are needed for his intellectual development.

While it is true that this development coming out of continuing education is a matter of individual responsibility, the engineering profession has come to realize that it can be of service to the young engineer in giving counsel and advice which will be helpful to him in his progress toward full professional recognition. This brings the writer to a description of a movement which has been growing steadily during the past two years and which has come to fruition in the formation of the Engineers' Council for Professional Development.

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[1] Vice president, American Telephone & Telegraph Co., New York, N.Y.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

Far-sighted engineers for a number of years past have been urging concerted action by the engineering societies, looking toward the enhancement of the professional status of the engineer. The investigation of engineering education carried on by the Society for the Promotion of Engineering Education stimulated the realization that there must be closer cooperation between the engineering schools and the engineering profession. About three years ago the American Society of Mechanical Engineers appointed a committee to investigate the economic status of the engineer. The report of this committee was read at the annual meeting of the Society in December 1931, by its chairman, Mr. Conrad Lauer. As bearing on the subject of this paper, the committee reported 2 significant conclusions. One was that more important than his economic status was the higher professional and social development of the engineer; the other, that an effort looking toward the enhancement of the profession and the development of the engineer would require joint action by all the major engineering societies.

Coincident with the submission of this report, Mr. Lauer became President of The American Society of Mechanical Engineers. He proposed a conference of the 4 founder societies and the Society for the Promotion of Engineering Education. The following is a short extract from his letter of invitation:

"Through this study (on the economic status) our committee has come to the realization that if the economic status of the profession is to be improved, the professional and social status must be improved as well. The profession itself must establish standards for selecting engineering students, must cooperate in their formal education, must take an important interest in their post-college training, and must provide a suitable goal of achievement.

"With this in mind our Council has approved a program entitled, 'Certification into the Profession,' a copy of which is attached, and has requested me to extend to you an invitation to appoint three representatives to meet with representatives of the other societies to discuss the possibilities of joint action, and initiate a program of such action."

The first conference, having for its membership 3 delegates from each of these 5 societies, met in February 1932, approved the proposal for joint action in principle, and directed the chairman to appoint a planning committee and to invite representation to a subsequent conference of 2 other organizations, the American Institute of Chemical Engineers, and the National Council of State Boards of Engineering Examiners. The Planning Committee prepared a report which was submitted at a conference meeting held on April 14, 1932, and the plan submitted for the professional development of the engineer was given careful consideration, revised somewhat, and approved by the conference. The action taken at this conference was to submit the plan for adoption to the Governing Boards of the participating organizations. The plan was submitted to the Societies at their spring and summer meetings, the final approval being recorded by the American Institute of Mining and Metallurgical Engineers on October 21, 1932, insuring participation of all 7 organizations. The list of participating organizations is as follows:

American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Mechanical Engineers, American Institute of Electrical Engineers, American Institute of Chemical Engineers, Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

The Engineers' Council for Professional Development is a conference of engineering bodies functioning to enhance the professional status of the engineer through the cooperative support of the national organizations directly representing the professional, technological, educational, and legislative phases of an engineer's life. To this end, it aims to coordinate and promote efforts and aspirations directed toward higher professional standards of education and practise, greater solidarity of the profession, and greater effectiveness in dealing with technical, social, and economic problems. As constituted, the Council has three delegates from each of the participating organizations.

The immediate objective of the Council is the development of a system whereby the progress of a young engineer toward professional standing can be recognized by the public, by the profession, and by the man himself, through the formulation of technical and other qualifications which will enable him to meet minimum professional standards.

The Council's program for professional development might briefly be described as follows:

First, to develop further means for the educational and vocational orientation of young men with respect to the responsibilities and opportunities of engineers, in order that only those may seek entrance to the profession who have the high quality, aptitude, and capacity which are required of its members;

Second, to formulate criteria for colleges of engineering which will insure to their graduates a sound educational background for practising the engineering profession;

Third, to develop a program for the further personal and professional development of young engineering graduates and a program for those without complete formal scholastic training;

Fourth, to develop methods whereby those engineers who have met suitable standards may receive corresponding professional recognition.

Concerning the method of operation, the Engineers' Council for Professional Development will, from time to time, recommend to the governing boards of the participating bodies, procedures considered to be of value or significance in promoting the general objective and will administer such procedures as have been approved by those boards.

Considerable progress has been made in the organization of the council. An executive committee has been appointed from the membership, composed of one member from each of the participating organizations. The organization of other committees is now in progress. Their duties are considered to lie in certain distinct fields, arranged in a time sequence contributing to the full development of the young engineer.

The Committee on student selection and guidance, as its name implies, will be responsible for developing ways and means to carry out the first element in the program. One significant contribution to the work of this committee already has been made through the publication by The Engineering Foundation of the booklet entitled, "Engineering—A Career, A Culture."

The committee on engineering schools will devote its efforts to bringing about a high degree of cooperation between the engineering profession and the engineering schools. This cooperation will be tendered by the profession in a spirit of helpfulness, with a full realization that the responsibility for the development of engineering education lies with the engineering schools. One undertaking which seems to require immediate attention is that set forth in the second item in the program—the development of criteria for colleges of engineering which will insure to their graduates a sound educational background for practising the engineering profession.

The committee on professional training will function on the third item of the program. It will endeavor to be helpful to the young engineer in arranging a program of personal development which will bridge the gap between graduation and full professional recognition. The major part of this program, of course, will be experience, gained in the practise of the profession. This committee can be of most service in suggesting subjects for study which will contribute most to intellectual development and which will prepare the young engineer to meet the requirements set forth by the committee on professional recognition.

Much study must be devoted to determining the average length of time which the graduate must spend in preparing himself for full professional status. It will depend largely on the qualifications decided upon. Tentative discussion within the Council would seem to indicate that this period might cover 5 years after graduation, or a longer period for those men who have not had complete formal engineering training.

The committee on professional recognition covering the fourth element in the program will set the goal for full professional status. Again much study must be devoted to the determination of objectives and a definition of the criteria which must be met. The nature of the award which will give evidence of full professional recognition must also be determined. Members of the Council, in preliminary discussion, suggested a number of awards, such as full membership in the professional societies, the granting of the professional degree by the engineering colleges, and licensure in those states requiring registration and license of engineers. In fact, professional recognition might include all three of these awards. Surely they are goals worth striving for, and will add much to the engineer's prestige.

Contemplating the program as a whole, it becomes evident that the Council is responsible for maintaining contact with the young man from the time he begins to think about his life's career, as an applicant at the gates of his chosen engineering college, as a student and graduate, through his novitiate of practical experience, and further intellectual development, until that time comes when he stands beside his fellows, recognized as a professional engineer. It covers a spread of fully 10 of the most vital years of a man's life. Here is a cause worthy of the devoted service of every member of the great national engineering organizations. When the program begins to function it will require the active participation of divisions, local sections and chapters, and student sections, as well as all engineering schools. Success demands the united wisdom of the whole profession.

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## Discussion

**D. C. Jackson:** The discussion aroused by this interesting and valuable paper by General Rees leads the writer to make a plea for support on the part of the engineering faculties (as well as the industrialists and practising engineers) for the new Engineers' Council on Professional Development; and also to give some information regarding the constitution of that Council.

As pointed out by General Rees, the Council consists of 3 representatives chosen by the governing boards of each of 7 societies, making a total of 21 members.

The Council has a fairly numerous representation of engineering faculties. The representatives of the Society for the Promotion of Engineering Education who are members of the new Council definitely represent that aspect. In addition thereto, several other societies have appointed members of engineering faculties among their representatives on the Council. Engineering education therefore is well represented in the membership of the Council. The writer does not fear that this important aspect of professional development will fail in receiving full attention from the Council.

The case of engineering education is a strong one but if it is not sufficiently strong to receive the degree of attention and support of the Council which it ought to receive, then it is desirable for those of us who are professionally associated with engineering education to review our case and make it so strong that it cannot fail to receive an appropriate recognition by the Council. We have recently made a definite review through the Board of Investigation and Coordination of the Society for the Promotion of Engineering Education, the results of which are reported in Volume I of the report of that Board which has been issued and in Volume II which will soon be issued. If there is any doubt of the strength of the case for engineering education as provided in the engineering schools the writer commends a review of that report, and feels sure that you will be convinced that the situation is good and the attainments high; and also that due thought is being given in the engineering schools to maintain these attainments and also to improve upon them as rapidly as circumstances warrant.

Assuming therefore that the status of engineering education is of a high order and that its achievements are formally laid before us in the aforesaid report, there may still be in the minds of some a question regarding the appropriateness of the personnel composing the Council. If such an attitude affects the mind of any one interested, I urge upon you to express your opinions to the Board of Directors of the American Institute of Electrical Engineers, who I feel sure will gladly receive and suitably act upon suggestions regarding suitable appointments as our representatives on the Council.

Moreover, long experience shows that the Council of the Society for the Promotion of Engineering Education is sensitive to the opinions of members of that society. If any who are members of that society doubt the wisdom of the selection of its representatives on the Engineers' Council for Professional Development, expressions of opinion sent to the Society through its Secretary will be appreciated and will be given full consideration.

Some of us are members of other societies such as the American Society of Mechanical Engineers, or perhaps the American Institute of Chemical Engineers or the American Society of Civil Engineers or the American Institute of Mining and Metallurgical Engineers, and if any such feel reservations regarding the appointments as representatives on the Engineers' Council it is appropriate in each instance to communicate with the governing board of the society concerned.

The Engineers' Council for Professional Development is a permanent body and the members are appointed for periods of 3 years, except that this first group has memberships retiring at the end of 1 year, at the end of 2 years, and at the end of 3 years, so that it is appropriate to express views at the present time respecting the appointees who may soon retire by virtue of the limitation of their first term. Hereafter an appointee will be designated by each society each year.

The National Council of State Boards of Engineering Examiners appoints its representatives from its official body. Those representatives are men of professional standing and influence and my contact with them makes me satisfied that they also recognize the importance of the engineering schools in professional preparation for the engineering field.

Taking it all in all I think we may well be satisfied with the arrangement of the new Engineers' Council for Professional Development, and I urge upon you the desirability of giving it full and adequate support. It is still new and its principles are not all yet established but it holds a field of great promise for enlarging the welfare of the engineering profession. All of us, through our society memberships have an opportunity for aiding in the selection of the representatives that compose the Council and thus guiding the determination of the principles which it will follow.

**Calvin W. Rice:** The writer takes the opportunity to emphasize an idea illustrated by the telephone industry. Professor Bell was an assistant in his father's school for the deaf in South Boston. He developed the telephone to help the deaf; he had no commercial motive. The writer has taken the pains to go to Washington and consult the original correspondence with his mother, in which he exclaims that he has found a device to help the deaf.

In this connection the writer wishes to pay a tribute to the telephone industry of which General Rees is such an outstanding representative. Starting with the conception of the telephone from altruistic motives, by Professor Bell, we have the industry based upon the invention guided in its policies by such men as Mr. Vail and General Carty. One's legal domicile is where he elects to make it. In this same manner one makes his work a profession by his attitude toward it. One is professional to the degree he has a sense of public obligations. The word profession implies an application of special knowledge to the use of others as a vocation, as distinguished from its pursuit of one's own purposes.

**Paul Cloke:** The writer believes it would be better to have the degree-granting power for the professional degree remain vested in the educational institutions rather than in any group representing the founders societies or industry. On the other hand it seems entirely fitting and proper that there should be the closest possible cooperation between founders societies and industries and the educational institutions in determining the fitness of any candidate for the degree.

Mr. Lamme said many years ago when he was Chief Engineer of the Westinghouse Company, that either an engineer was born or else received a very definite trend that way at a comparatively early age. It has been noteworthy to see the proposals being brought forward by educators in the State of Pennsylvania that a complete record of a student's progress through high school be maintained noting development not only scholastically but morally and physically. In fact there are a very large number of factors which are to be charted. The results of such information, which could be furnished by high school teachers, would be of distinct help in determining whether or not a student should enter an engineering course.

In the State of Maine there is good cooperation between the high schools and the university along general lines although nowhere near as specific as proposed by the Pennsylvania educators. For example, the writer placed one of the pamphlets entitled "Engineering—A Career, A Culture" in every high school of any consequence and in the hands of each engineering freshman.

**Joseph Weil:** In discussing the various modes of recognition given engineers, particular emphasis should be placed upon the importance of a more unified mode of procedure for granting the professional degree of electrical engineer. At the present time, in many cases, this degree means very little, in so far as the recognition of professional attainment is concerned. At the University of Florida, a survey was made of the requirements for this degree and it was found, as expected, that there is a very wide variation in the requirements of different colleges. This university has now materially increased its requirements for the professional degree, and now requires a minimum of five years of responsible work following graduation, a thesis and examination. The college recognizes that the thesis and examination may prevent some alumni who are qualified from applying for this degree, but it hopes to be able to have most of its alumni feel that the degree is well worth having, and therefore have them apply for it.

The difficulty that the college might have in determining the character of responsible work was clearly recognized and it has been conceded that one way in which the applicant can meet this requirement is by securing registration in the State of Florida. In this connection, it may be of interest to note that the National Board of Engineering Examiners has recently proposed a method of accrediting engineering colleges. Has the Engineering Council for Professional Development been consulted in this regard?

**George A. Irland:** It is recognized that a four-year college course is not sufficient training to produce a professional engineer. Considerable experience, in addition to the college course, is required. Why then should any college grant the degree of engineer upon graduation from a four-year course?

It is the writer's belief that the granting of a professional degree should not be abandoned, but that its significance should be increased by granting it only to those qualified by their training to be termed professional engineers. This degree would have a different meaning from the Master's or Doctor's degree. No amount of graduate study can replace the kind of training obtained in practical work, and it seems that the man who has received his training while engaged in responsible engineering work should be granted a professional degree, and that such a degree should be as highly honored as degrees conferred for academic training.

# A Recent Development in High-Current Mercury Arc Rectifiers

BY E. H. REID* and C. C. HERSKIND*
Non-Member Associate A.I.E.E.

***Synopsis.***—*A single-unit mercury arc rectifier of 3,000-kw rating at 600 volts is discussed as regards design and operation. A typical installation, that of the 8th Avenue subway of the New York Board of Transportation, is described where units of this size have been advantageously applied to the sub-surface substations.*

*An important characteristic of the rectifier unit is its operating temperature which is materially higher than heretofore used in general practise. Tests show that up to a certain temperature the arc drop is reduced as the temperature is raised. This indicates that the maximum efficiency is obtained by operating at a high temperature. Among other advantages of a high operating temperature is the increased cooling efficiency.*

*The rectifier is of the thyratron type with insulated grids surrounding the anodes. In addition to straight rectification, it is expected that it will find many applications in the future where thyratron control is desired.*

A HIGH-CURRENT mercury arc rectifier in single-unit form is one of the recent developments in conversion apparatus. A reliable unit with a nominal rating of 3,000 kw at 625 volts and having overload ratings up to 300 per cent full-load current has been made available for commercial applications. Some of these units are now in operation on the new 8th Avenue subway in New York City. Others are installed on railway systems and in electrolytic plants. This size and type of unit was first developed to fill traction system requirements for a compact and reliable power unit having high overload capacity. However, it is expected to find a wide variety of industrial applications because of its high overall load efficiency, quietness of operation, adaptability to grid control and other desirable characteristics.

Many of the advantages of mercury arc rectifiers have been realized in their application to the power system for the New York Board of Transportation subways. Their use has made possible the location of the substations underground and adjacent to the subway tracks. A considerable saving was effected by this arrangement since the substations could be located under the city street thus obviating the purchase of valuable property for substation sites. Fig. 1 shows a view of the 3,000-kw, 625-volt rectifier unit and Fig. 2 shows a typical installation in one of the automatic underground substations of the New York Board of Transportation. These substations consist of a single room built of reenforced concrete and containing the transformers, switchgear and all other equipment required in connection with the operation and control of the rectifier. A simpler, more compact, and less expensive substation construction is obtained by the use of rectifiers instead of synchronous converters. Heavy foundations are not necessary as the rectifier has no rotating parts and is light in weight. Also since water can be used for cooling, no expensive duct system and ventilating equipment is required. With rectifiers, the fire hazard is reduced and the noise problem eliminated. Altogether, the rectifier forms an ideal conversion unit for underground installation.

The design of the high-current rectifier is based on the principles evolved by the intensive investigation and research on mercury arc rectifiers. Some of these principles have been outlined in the recent paper on *Mercury Arc Rectifier Research*† presented by A. W. Hull and H. D. Brown. Further tests have been made to determine the limiting values of the various factors

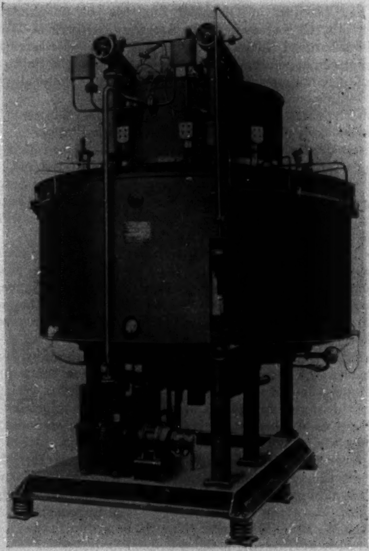

Fig. 1—Front View of 3,000-Kw, 625-Volt Mercury Arc Rectifier

involved in a design for heavy currents. These tests together with considerable data obtained from the various sizes of rectifiers operating successfully in the field were used in arriving at the new design.

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*General Electric Co., Schenectady, N. Y.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 23-27, 1933.*

†A.I.E.E. Trans., Vol. 50, Part 2, 1931, p. 744.

The form of the 3,000-kw tank is similar to that of previous rectifier designs except for the changes required by the greatly increased rating. The rating of a rectifier may be increased by raising its operating voltage without changing greatly its overall dimensions. The design of a high-voltage rectifier is mostly a matter of general placement, spacing, and insulation of the various parts. On the other hand, increasing the current rating involves the enlargement of the tank and its parts. The size of a rectifier is determined chiefly by its current rating as the losses in a mercury arc are almost directly proportional to the load current. This means that for increased current capacity the condensing area must be greater and the current carrying parts must be enlarged. In making these changes care must be taken to provide an arc path of the proper dimensions between anode and cathode. If the arc stream is greatly lengthened or the arc area is made too small the arc loss will be increased and part of the advantage of the larger unit will be lost.

Fig. 3 is a cross sectional view showing the arrangement of the internal parts in the New York Board of Transportation rectifier. The vacuum chamber consisting of the lower tank and the dome constitute the greater part of the effective condensing area. The water coils in the lower section and in the dome form about one-third of the total effective condensing area. Ample cooling area has been provided to maintain effective control of the vapor pressure at all loads. Cooling coils afford a very inexpensive way of increasing the cooling area and the overload capacity of the rectifier. A rectifier vacuum chamber having the same condensing area without cooling coils would be much larger in size and would have greater spacing between electrodes.

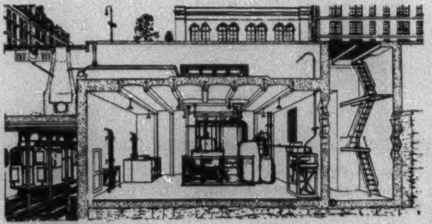

Fig. 2—Sectional View of Typical Subsurface Mercury Arc Rectifier Substation for the Board of Transportation, City of New York

The current carrying capacity of a given rectifier is determined among other things by the mercury vapor pressure, or, practically speaking, the operating temperature, and the cross sectional area of the anode arms. By furnishing proper baffling surfaces and dividing the arc into small streams reliable operation can be obtained at higher temperatures. When the rectifier is so baffled, the maximum current which can be carried increases uniformly with increase in temperature, within a certain temperature range, and is directly proportional to the cross sectional area of the anode arms. The cross section area of the anode arms is fixed largely by the maximum desired overload rating of the rectifier.

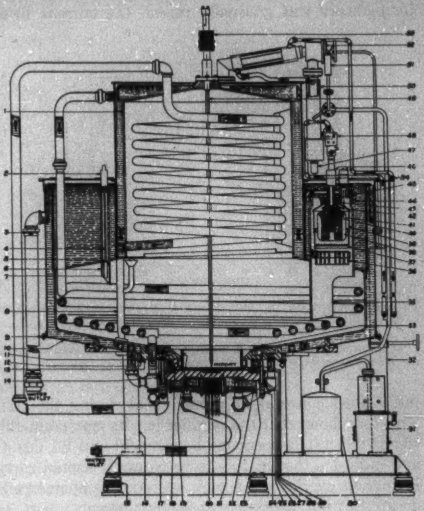

Fig. 3—Cross Sectional View of 3,000-Kw, 625-Volt Mercury Arc Rectifier

1 Vacuum chamber
2 Excitation anode seal
3 Overflow graphite nipple
4 Excitation anode stud
5 Excitation anode stop nut
6 Excitation anode shield
7 Excitation anode tip
8 Mercury drain strut
9 Cord
10 Tank water jacket
11 Tie ring outer gasket
12 Tie ring
13 Tie ring inner gasket
14 Cathode
15 Base insulator
16 Leg
17 Rectifier base
18 Cathode outer shield
19 Cathode inner shield
20 Cathode stud
21 Cathode bottom plate inner gasket
22 Cathode bottom plate outer gasket
23 Cathode bottom plate
24 Cathode spring
25 Steel washer
26 Insulating washer
27 Supporting stud insulating tube
28 Cathode supporting stud
29 Cathode insulator
30 Gas receiver tank
31 Rotary vacuum pump
32 Vacuum gage
33 Trash rack
34 Carbon tip nipple
35 Main anode shield
36 Main anode baffle
37 Main anode grid
38 Main anode tip
39 Main anode grid support
40 Main anode stud
41 Main anode stop nut
42 Cone baffle
43 Insulator
44 Clamping ring
45 Main anode space ring
46 Grid and main anode seal
47 Mercury condensation pump heater
48 Main anode terminal
49 Ignition anode rod
50 Mercury condensation pump
51 Mercury trap
52 Accordion vacuum valve
53 Ignition anode coil

Sufficient arc section must be provided to carry the peak anode currents without excessive arc drop.

As the temperature is increased, up to a certain value, the arc drop is lowered. In this rectifier full advantage has been taken of this factor as can be seen from the curve shown in Fig. 4. This curve was obtained by taking arc drop readings on a rectifier as its operating temperature was gradually raised, the current being maintained constant at normal load during the test. This test shows that the rectifier has its maximum efficiency when it is operating between 70 and 80 deg C and indicates that at this temperature it should carry its highest overloads. A high operating temperature is desirable from another standpoint, namely, that of cooling efficiency. A reduction in water consumption to from one-third to one-half of that required by other designs has been made possible by the increase in operating temperature.

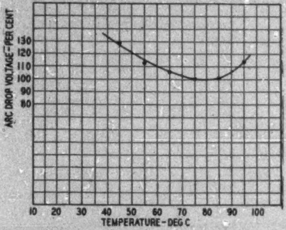

Fig. 4—Variation in Arc Drop Voltage with Operating Temperature on a Rectifier Carrying Normal Load

Arc drop expressed in per cent of normal arc drop at full load and normal operating temperature

The thyratron type of anode construction is used, with graphite anodes, mycalex seals, subdividing baffles, and insulated grids. The anode assembly is shown in Fig. 5. The anode tip, which is of graphite, is supported from the vacuum chamber by means of the insulating mycalex seal. It is surrounded by an insulated shield which supports the grid. The grid, which is also of graphite, is placed in front of the anode so that the arc must pass through it to reach the anode. It consists of a flat disk perforated with a large number of small holes very closely spaced in order to obtain a large percentage of the total area for the passage of the arc. An insulated lead is brought out from the grid through a small mycalex seal so that a separate potential may be applied to the grid. Below the anode and grid is located the subdividing baffle, which consists of a number of concentric steel rings supported from arms welded to the walls of the anode housing.

An improvement in high-current rectifiers has been obtained by the addition of a trash rack. This is installed in the vacuum chamber just above the cathode so that the condensed mercury must pass through it when returning to the cathode. It serves two purposes. First, it collects all dirt and foreign matter floating on the returning mercury, thereby gradually cleaning the vacuum chamber and preventing contamination of the mercury in the cathode. Second, by means of small holes or weirs it distributes the returning mercury so that it will not flow in one large stream which might produce a short circuit between the vacuum tank and the cathode. The importance of this factor will be seen when the amount of mercury circulated in the tank is considered. At 300 per cent load the rate of evaporization of mercury from the cathode is approximately fourteen pounds per minute. In addition to the trash rack a system of troughs and pipes is provided to catch the mercury condensed in the dome and return it to the cathode thus lessening the possibility of splashing.

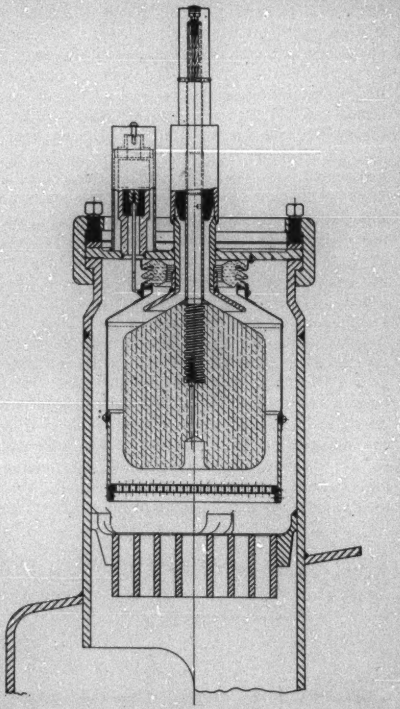

Fig. 5—Vertical Sectional View of Anode Housing and Anode Assembly for 3,000-Kw, 625-Volt Mercury Arc Rectifier

Showing mycalex seal graphite anode, insulated grid and subdividing baffle

The rectifier is designed for a-c ignition and excitation. A single plunging anode is used for ignition and three small graphite anodes for the excitation arc. The insulated grids are excited with a d-c bias in order to supplement the holding anode excitation and aid pickup. The exhaust system consists of two mercury condensation pumps operating in parallel and connected to one rotary oil roughing pump. Exhaust is from the dome where the foreign gas tends to collect under the combined action of the arc and condensing mercury. Vacuum is measured by a McLeod gage in one exhaust line and a hot wire manometer gage in the other.

A number of novel features are incorporated in the cooling system used on the New York Board of Transportation rectifiers. A diagram of this system is shown in Fig. 6. It is a recirculating system with a water-to-water heat exchanger. The rectifier cooling water is circulated continuously by means of a centrifugal pump. The heat imparted to the cooling water while flowing through the rectifier is carried away by the tap water flowing through the heat exchanger. The high operating temperature of the rectifier has made it possible to connect the transformer and rectifier tap water systems in series, the water flowing through the transformer cooling coils first, then into the heat exchanger and finally discharging into the drain. A further saving in cooling water is obtained by this arrangement. The flow of water is regulated by means of two temperature controlled valves, one of which is actuated by the rectifier and the other by the transformer temperature. The valve controlling the flow of water through the heat exchanger is actuated by a bleeder circuit which is connected to the rectifier at the point of most rapid temperature fluctuation. A very accurate control of temperature at all loads is secured by this system. At light load no cooling water is required by the rectifier so its valve closes. The valve actuated from the transformer then opens a bypass into the drain permitting a flow of water through the transformer alone, to carry away the core losses.

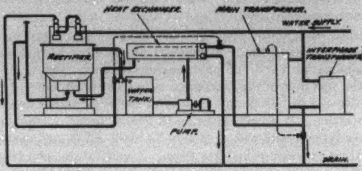

Fig. 6—Schematic Diagram of Closed Cooling System Used with Rectifiers for New York Board of Transportation

The use of a heat exchanger with a recirculating system permits the discharge into the drain to be located at a higher level without applying pressure to the rectifier. This is desirable where the rectifier is installed in an underground substation. By means of the circulating pump a large flow of water can be obtained at all loads, providing efficient cooling and assuring a uniform temperature. The closed system permits ready treatment of the cooling water with solutions for prevention of corrosion.

The 3,000-kw units installed on the New York Board of Transportation rectifiers are arranged to operate as simple rectifiers with 5 per cent shunt regulation. They are connected to a 12-phase zig-zag-connected power transformer with an interphase transformer.

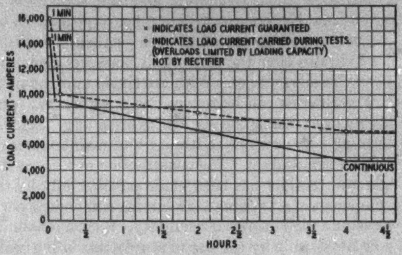

Fig. 7—Load Current *vs.* Time Curve of 3,000-Kw, 625-Volt Rectifier

Straight rectification is only one of the many possible applications of this high-current rectifier unit. By proper excitation of the control grids it may also be used as a power thyratron. The grid has been designed with suitable characteristics for power control purposes and has a control ratio of power controlled to control power of almost 100,000 to one. Among the many applications for which this thyratron power unit is adapted are; voltage regulated d-c power output, high-speed circuit breaker, inverter, and static frequency changer.

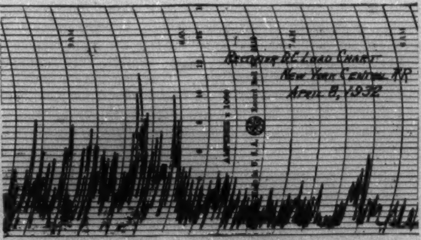

Fig. 8—Typical Load Chart of 3,000-Kw Unit Operating on New York Central Railroad

That these rectifiers have ample load capacity has been proved both by tests in the factory and by field experience. The rectifier is guaranteed for the following load ratings; 150 per cent for two hours, 200 per cent for five minutes and a momentary overload of 300 per cent full-load current for one minute. Fig. 7 shows the overloads carried on the rectifier with the loading facilities available in the factory. These overloads do not represent the limit of the rectifier. Fig. 8 is a load chart taken on a 3,000-kw unit operating on the New York Central Railroad indicating the character of load which may be expected in traction service.

The operation to date of rectifiers of this size has demonstrated their reliability and the soundness of their design. Experience for a number of years with the construction and operation of both single and multiple units indicates that the single unit possesses a number of desirable advantages. With the single unit the number of auxiliaries can be reduced to a minimum. This is highly desirable as the auxiliaries are a large factor in determining the overall reliability and maintenance on a rectifier installation. The construction of a successful single unit rectifier has been made possible only by the development of a vacuum tank having component parts possessing a high degree of reliability. Such a reliability is now obtainable by the use of sturdy insulating seals, improved welding, indestructible graphite parts, proper placement of parts, and latest manufacturing technique. These factors have contributed largely to the success of the high current single unit rectifier.

## Discussion

**J. J. Linebaugh:** Very few engineers appreciate the difficulties encountered by the designing engineer in designing a reliable mercury arc rectifier, particularly one with as great a capacity as the one described by Messrs. Reid and Herskind. The ampere ratings of this unit give one a better idea of the problems encountered than the kilowatt rating with overloads. The continuous ampere rating of 4,800 amperes at 625 volts, 7,200 amperes for two hours, 9,600 amperes for five minutes and 14,400 amperes for one minute indicates clearly that the whole unit must accurately and conservatively be designed to rectify such currents.

It requires a careful balancing of vacuum, anode and cathode currents per square centimeter, spacing, heat and voltage gradients, insulation, vacuum tight tank, baffles, and adequate cooling to produce a satisfactory rectifier. In addition the engineer can not see what is happening inside the tank, making it difficult to determine the cause of the trouble. The engineers should feel gratified with the success that they have attained.

The magnitude of the New York Board installation mentioned is indicated by the fact that over sixty 3,000-kw units have been purchased already and more will be ordered as the subways are extended.

The cooling system used merits attention as it is very economical of water. The use of the fairly high temperature cooling medium combined with the use of the cooling water from the transformers makes this possible. Data obtained this far indicate about 0.15 gallon of water per minute per 1,000 amperes for the load factors now obtained.

The use of the thyratron principle with excited grids is a new departure for rectifiers of this ampere capacity although the same design was used on the 3,000-volt Lackawanna rectifiers. It should be noted that the grids are not used for voltage control.

The New York Board rectifiers have slightly more than the usual regulation to accommodate them to the one unit layout used for most substations and to make them self-protecting from extreme overloads by dividing the total load with adjacent substations.

Operation this far indicates that the rectifiers easily will meet all requirements of regular service without difficulty.

**E. H. Reid and C. C. Herskind:** The paper describes one of the latest contributions to the rapidly advancing development of mercury arc rectifiers. This high capacity unit extends the range and type of applications for which rectifiers are available, as it is not merely a rectifier. It is also a power thyratron, for, by utilizing the grids with which it is provided it may be operated to supply regulated d-c output, for inverting, for frequency changing, and a number of other purposes. Up to the present time the possibilities of the power thyratron have not been commercially realized to any appreciable extent. However, it is expected that the development of this power unit will do much to hasten thyratron applications.

As has been stated the 3,000-kw 600-volt unit was developed primarily to meet the requirements of the New York Board of Transportation for a compact conversion unit. Inasmuch as it was the first unit of this particular type to be built, ample margin was allowed in the design factors in order to assure reliability of operation. Without changing the basic factors in this design, further refinements will of course be made on future designs as operating experience justifies them. Modifications can be made which will effect savings in manufacturing cost and reductions in rectifier losses.

The paper points out the importance of operating temperature as a factor in rectifier design and operation. This factor will become more important as the specific loading on the rectifier is increased and the size for a given rating is reduced.

The reliability of this unit has been proved by considerable operation in actual service. For example two of these units are operating in an electrolytic plant where they carry full load continuously. They have operated for several months with a station factor of approximately 99 per cent. In factory tests at 1,500 volts, one of these units carried 4,000 amperes continuously, 6,000 amperes for 2 hours and 12,000 amperes for 1 minute. These tests indicate that the unit has ample capacity for a nominal rating of 6,000 kw at 1,500 volts. This rating is desirable for a number of thyratron applications.

# Synchronous-Mechanical Rectifier-Inverter

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## Introduction

THE object of the development described in this paper has been to so modify and equip the synchronous commutator of the short-circuiting type[1,2] as to enable it to perform the two functions of rectification and inversion interchangeably under conditions of comparatively high voltage and current. An outstanding effort toward the solution of this problem was the Calverley-Highfield "transverter."[3] Mr. Sewall Cabot[4] contributed to this art by employing a quadrature voltage component of fundamental frequency for the purpose of aiding commutation.

The features added to the construction and application of the short-circuiting rectifier are as follows:

1. The rotor is so simplified and designed as to contain nothing but $n + 1$ insulated metallic segments, $n$ being the number of a-c phases. These segments perform the functions of properly orienting the phase voltages within the d-c circuit and of producing short-circuiting periods during which commutation occurs.
2. Each phase voltage is made substantially zero at the beginning and the end of the commutation period by the introduction of a negative in-phase 3rd harmonic voltage $E_n$.
3. A quadrature 3rd harmonic voltage $E_r$ is used to cause current reversal in the a-c phases.
4. Means are provided for making $E_n$ proportional to the a-c system voltage and for making $E_r$ proportional to the d-c load.

The use of the harmonic voltage $E_r$ during an extended commutating period makes possible the successful reversal of large currents flowing in highly reactive circuits. This is accomplished entirely under cover and with no visible sparking. The harmonic voltages importantly modify the a-c wave form and the extended commutation period causes a reduction in d-c to a-c voltage ratio.

## Description of Element

The connections of an element for single-phase use are shown in Fig. 1e. The a-c system includes the generating source $G$, the armature of the 3rd harmonic generator $H$ and the transformer primary coil $L_1$. The secondary coil of the transformer $L_2$ with a condenser $C$ across it has its terminals connected to the stationary brushes $B_1$ and $B_2$. The rotor segments $S_1$ and $S_2$ have an angular overlap $\alpha$ corresponding to a half cycle of the 3rd harmonic of voltage. These segments communicate either by means of extra brushes or by extra collector rings with the d-c system which is here represented as a d-c dynamo $D$. The steadying reactance $X$ is essential for single-phase operation in order to prevent a short-circuit of the d-c system during the commutation period. This reactance may be dispensed with in the polyphase rectifier unless it is desired to smooth out the ripples in the direct current. The physical arrangement of rotor segments and twin brush sets may best be understood by reference to Fig. 4 which illustrates the three-phase application.

The points at which current measurements and oscillograms have been taken and which are referred to later are:

$I_t$ = transformer or a-c system current.
$I_a$ = alternating current to or from rectifier.
$I_c$ = condenser current.
$I_d$ = direct input or output current.
$I_n$ = current in transformer neutral (3rd, 9th, etc., harmonic when in three-phase operation).

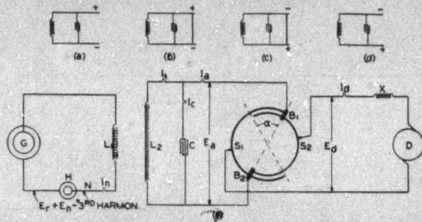

FIG. 1—SINGLE ELEMENT OF RECTIFIER-INVERTER

## Operation of Element as a Rectifier

It is necessary to have a clear understanding of the manner in which one of these elements functions in order to appreciate the performance of the rectifier-inverter when in polyphase operation.

The a-c system is assumed to supply a sinusoidal voltage of fundamental frequency to which are added two 3rd harmonic components, $E_n$ and $E_r$. The segments $S_1$ and $S_2$ of the rectifier are assumed connected in some manner with an active d-c system such as a d-c generator driven by an a-c motor supplied from a system capable of giving or receiving power. The rectifier rotor and the generator introducing the harmonics $E_n$ and $E_r$ are synchronously driven from the a-c supply either by individual motors or by a single motor. The sequence of connections among transformer, condenser, d-c terminals and short-circuit is indicated by $a$, $b$, $c$ and $d$ of Fig. 1. Connections $a$ and $d$ correspond to the positive and negative "working" periods respectively

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1. For numbered references see bibliography.

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and connections *b* and *c* to the intermediate commutation period.

Fig. 2 is drawn to show the variation of the several voltage and current components previously mentioned. These components are all laid down on a percentage basis and result from the calculations of a hypothetical problem referred to later. The figure represents the case of nominal load rectification. The currents plotted are indicated by symbols corresponding to the points of measurement of Fig. 1e.

The fundamental sinusoidal voltage supplied by the a-c system $E_1$ is taken as 80 per cent, the total a-c system reactance having been assumed as 20 per cent. A single half wave of the reversing voltage $E_r$ is shown in its proper phase. The same is done for the neutralizing voltage $E_n$. The sum of all the voltages supplied from the generating sources is shown as $E$. It will appear that negative values of $E$ predominate during the commutation period 3-4. It is this excess of negative voltage that is instrumental in causing the current in the a-c system to reverse when the transformer is short-circuited.

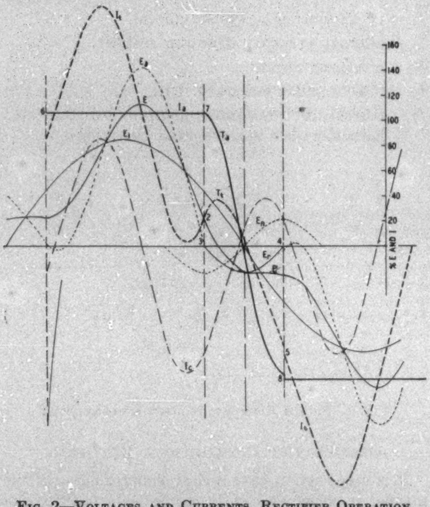

FIG. 2—VOLTAGES AND CURRENTS, RECTIFIER OPERATION

The fundamental condenser current $I_{c1}$ (not shown in the figure) is calculated by using the fundamental voltage $E_1$, the fundamental frequency reactance of the a-c system, and the capacitive reactance of the condenser. The inductive reactance used includes the transformer leakage reactance and the transient reactances of the fundamental and harmonic generators. All resistances are ignored.

The 3rd harmonic condenser current $I_{c3}$ is calculated from the resultant of $E_n$ and $E_r$ and the triple frequency reactance of the *L-C* circuit. The condenser capacitance must be small enough to make this current leading.

$I_c$ represents the total resultant condenser current and is plotted as a steady-state function across the short-circuit period in order to indicate its form when uninterrupted by that period.

For the purpose of this discussion, the alternating current to the rectifier $I_a$ is assumed constant during the working period. Experiments have shown that this current makes a "transit" or reversal from positive to negative along a path (7 to 8, Fig. 2). This indicates that the current transfers occurring under the brushes are gradual and do not result in excessive momentary densities. The current $I_a$ can be caused to remain constant during the working cycle by using a high value of steadying reactance in the d-c circuit. When no reactance is used, this current follows the d-c voltage form.

The current in the transformer coil $I_t$ must necessarily be the sum of $I_a$ and $I_c$. When this is plotted for two successive working periods, it becomes apparent that the net transit required during the commutation period is reduced from 7-8 to 2-5 in the figure. When the transformer is short-circuited, the a-c system current changes under the influence of three electromotive forces $E_1$, $E_n$ and $E_r$. The first two, acting in opposite directions during the short-circuit period and passing through zero at the neutral axis, cause a positive pulse in the current curve. $E_r$ causes a rate of decrease of the current which is a sine function of time. The portion of the $I_t$ curve within the commutation limits is termed the "transit" of $I_t$ and is marked $T_t$ in the figure.

The a-c terminal voltage $E_a$ which exists across the transformer, condenser, and rectifier simultaneously is obtained by adding to the values of $E$ from the generating sources the instantaneous values of $- L \frac{di_e}{dt}$ where $L$ is the inductance corresponding to the total a-c system reactance. It should be noted that $E_a$ may be caused to pass through zero at the points 3 and 4 so that the commutation period is entered and left without voltage and therefore without shock.

## OPERATION OF ELEMENT AS AN INVERTER

The element, the rectifying action of which has just been described and illustrated by Fig. 2, will act as an inverter if the d-c voltage $E_d$ is raised above the corresponding a-c voltage $E_a$ or if $E_a$ is lowered when $E_d$ remains constant. When inversion takes place, there will occur a reversal of the direct current $I_d$ and of the phase of the alternating current $I_a$. The phase of the 3rd harmonic commutating voltage $E_r$ must also reverse and be proportional to the load current transmitted. This proportionality and phase reversal is secured by having the field of the generator furnishing $E_r$ connected in series with the d-c line carrying $I_d$.

Fig. 3, for the case of inversion, has been drawn from values calculated for the hypothetical problem. The operating conditions are the same as for the case represented by Fig. 2 except that the reversals mentioned in the preceding paragraph have taken place. Since the phase of $I_a$ is now opposed to that of $E_1$, the flow of power has reversed. A comparative study of Figs. 2 and 3 will reveal a perfectly symmetrical correspondence between the various voltage and current forms for the two cases of operation. These forms undergo a gradual transition when the load changes as is shown by oscillographic records of Fig. 12.

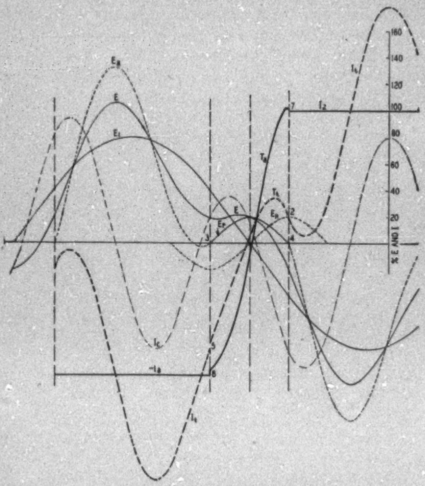

FIG. 3—VOLTAGES AND CURRENTS, INVERTER OPERATION

When the load on the apparatus is zero (neither rectifying nor inverting) which condition obtains when there is a perfect balance of a-c and d-c voltages, the transformer current ($I_t$) will consist of the steady-state condenser current modified by certain surges during the short-circuit period.

## THREE-PHASE APPLICATION

Three or more elements of this rectifier-inverter may be caused to operate in series by the use of a rotor arrangement such as shown in Fig. 4. The contact segments ($S_1$ to $S_4$) are so arranged as to permit one of the intermediate segments $S_2$ to function on two a-c phases so that the number of segment disks will be one more than the number of phases. The connections of the transformers, condensers and twin brush sets are shown by the figure. The d-c lines $D_1$ and $D_2$ may be caused to contact with the terminal segments by means of additional brushes sliding on the latter. This rotor construction will be roughly balanced statically but not dynamically. The four-pole arrangement of such a rotor would be well balanced dynamically.

When a rotor of the above description operates from a three-phase supply, the result is the orderly insertion of the individual transformer secondaries $T_1$, $T_2$ and $T_3$ into the d-c circuit, their withdrawal by short-circuit during the period of reversal, and their reinsertion in reversed sense thereafter. The average d-c voltage will thus be determinable from a knowledge of the contributions by each of the phase voltages. Sufficient reactance placed in the d-c line to filter out the ripples will result in a sensibly constant direct current for either direction of operation.

## COMPLETE EQUIPMENT

A complement of equipment for three-phase a-c to d-c conversion or vice versa is shown in Fig. 5 in which $G$ represents the a-c generating source supplying a bank of transformers with their low-tension coils star connected and their high-tension coils leading to the condensers and the rectifier brushes. The armature of a 3rd harmonic generator $A_h$ is connected into the neutral of the power system. This generator is driven by a synchronous motor $M$ and has two field coils producing two voltage components relatively in quadrature in $A_h$. The field $F_r$, in series with the d-c output of the rectifier, furnishes the reversing component $E_r$. This field may be shunted by $S$ to obtain adjustment in the value of $E_r$. At nominal load, the field $F_r$ must cause low magnetic saturation so as to be able to maintain approximate proportionality between $E_r$ and load current up to the value found on short circuit. The field $F_n$ supplying the

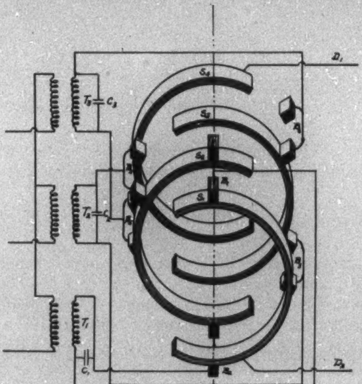

FIG. 4—THREE-PHASE ROTOR, PHASES IN SERIES

neutralizing voltage $E_n$ should be excited in proportion to the a-c system voltage. A mercury-arc rectifying equipment is shown as a convenient way of accomplishing this result. The strength of this field is a maximum at no-load and approaches zero on short circuit.

Transformer taps permit the regulation of the a-c voltage delivered to the rectifier without the necessity of disturbing the system voltage; by means of these, the flow of power may be arbitrarily controlled. Without transformer ratio adjustment, the power flow will automatically vary with the relative voltage levels on the d-c and a-c sides of the apparatus.

### THE REVERSING VOLTAGE $E_r$

A simple equation for the maximum value of the 3rd harmonic commutating or reversing voltage $E_r$ has been derived. The current change in the a-c system when short-circuited during commutation is given by

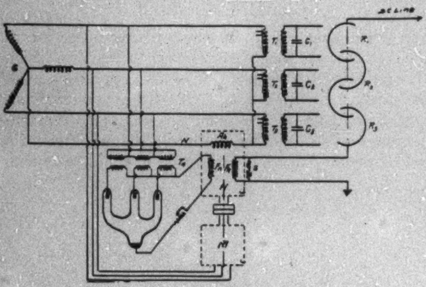

FIG. 5—COMPLETE SYSTEM, RECTIFIER-INVERTER

$$\Delta i = \frac{E_r}{w_3L}\int_0^{\pi} \sin w_3t \, dw_3t = \frac{2}{w_3L} E_r^* \qquad (1)$$

Reference to Fig. 2 will show that the actual change of current to be caused by $E_r$ is from point 2 to point 4 which amounts to $2\,I_d - 2\,I_r$ where $I_r$ is the maximum of the 3rd harmonic condenser current caused by $E_r$. Equating these two values of $\Delta i$ and remembering that $I_r = Y_3E_r$, $Y_3$ being the triple frequency admittance of the $L$-$C$ circuit, there is found

$$E_r = \frac{I_a\,(= I_d)}{\dfrac{1}{w_3L} + Y_3} \qquad (2)$$

From equation (2) it is seen that $E_r$ must be proportional to the load current and that its value is affected by the constants of the equivalent $L$-$C$ circuit considered to exist between the condenser and the a-c system reactance. This equation has yielded correct values of $E_r$ for a large number of experimental circuits.

### THE NEUTRALIZING VOLTAGE $E_n$

Fig. 6 shows a commutation period with the relative phase positions of the three voltages $E_1$, $E_n$ and $E_r$ acting within the short-circuited a-c system. The lines $S'S'$ and $F'F'$ represent respectively the beginning and the end of the short-circuit period when this is taken as covering 60 fundamental degrees. The lines $SS$ and $FF$ indicate the same limits for a shorter period. Each of the voltages produces a leading current component. These components are designated similarly as $I_1$, $I_n$ and $I_r$ and are shown dotted.

$E_n$ should have such a value as to make the terminal voltage across the condenser zero at the time when the short-circuit period is entered and left. The proper value for $E_n$ may be found by equating all the voltages acting in the circuit at these times to zero and solving for $E_n$. Assuming the 60-degree period, all the voltages acting at the beginning of short-circuit may be written as follows:

$$\left.\begin{array}{lll} -L\dfrac{di_1}{dt} = w_1L\dfrac{E_1}{X_1}\cos 60\text{ deg} & & \\ & & \text{(positive)} \\ -L\dfrac{di_r}{dt} = 0 & & \\ -L\dfrac{di_n}{dt} = -\,w_3L\dfrac{E_n}{X_3}\cos 0 & & \\ \qquad (= E_n \text{ approx.}) & & \text{(negative)} \\ e_1 = E_1 \sin 30\text{ deg} & & \text{(positive)} \\ e_r = 0 & & \\ e_n = -\,E_n & & \text{(negative)} \end{array}\right\} \Sigma = 0 \qquad (3)$$

so that

$$-\,E_n = 1/2\left(e_1 + L\frac{di_1}{dt}\right) \qquad (4)$$

Neglecting the term $L\dfrac{di_1}{dt}$ as relatively small, $E_n$ is found to be half of the value of fundamental voltage occurring at the beginning of commutation. Since both the terms $e_1$ and $L\dfrac{di_1}{dt}$ are proportional to the fundamental voltage $E_1$ it follows that $E_n$ should be proportional to the a-c system voltage at the rectifier.

When the commutation period is assumed to be shorter than 60 degrees, the six terms in equation (3) enter into the determination of the value of $E_n$; the result obtained is more complicated and the variation of $E_r$ with load less satisfactory. The solution is possible, however, and has been worked out for such periods.

### POWER TRANSFERS ON MOTOR-GENERATOR SET

The generator armature injecting the harmonic voltages into the neutral carries a current the greater part of which is in quadrature with the resultant induced voltage. Careful analysis has shown that there exists one component of this current that is in strict phase opposition with $E_r$ and is of the same frequency. This component is derived from the transit $T_t$ of Fig. 2. The commutation periods of the three phases are adjacent to each other in point of time so that the pulses or surges of successive transits give rise to alternately positive and negative half-waves of current in the neutral. For rectifier action, these current waves are in phase opposition to $E_r$ so that their interaction represents negative electrical power. In other words, the armature $A_h$ of Fig. 5 is motoring. Space does not permit the presentation of the analysis to show that this power transfer is the only one occurring.[5]

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*Maximum amplitudes of voltages and currents are assumed throughout this discussion.

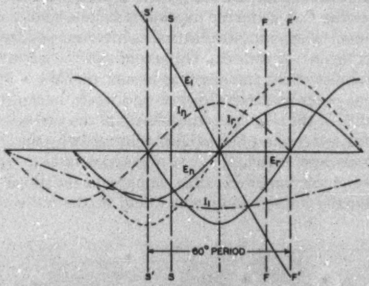

FIG. 6—PHASE RELATIONS OF HARMONIC VOLTAGES AND CURRENTS

The maximum of the pulse in the transit $T_t$ may be found from the equation

$$H_t = \frac{E_1}{\omega_1 L}\int_0^{\frac{\pi}{6}} \sin \omega_1 t\, d\omega_1 t - \frac{E_n}{\omega_3 L}\int_{\frac{\pi}{2}}^{0} \sin \omega_3 t\, d\omega_3 t \quad (5)$$

Since $H_t$ represents the maximum of a sine function, the average power transfer is given by

$$P_{av} = -\frac{1}{2} H_t E_r \quad (6)$$

When the apparatus is inverting, the phase of $E_r$ reverses while that of the 3rd harmonic current in the neutral resulting from the transits does not, so that the armature of the harmonic machine is now generating.

From the solution of a hypothetical problem representing the case of a practical installation of high kva capacity, the power transfer required of the motor-generator set at nominal load proved to be about 1.7 per cent of nominal rating. The maximum power demand occurring at 2.5 times nominal load was about 50 per cent greater or 2.55 per cent.

## RATINGS OF THE MOTOR-GENERATOR SET

The nominal *rating of the motor* would need to be the above mentioned 1.7 per cent of nominal kva of the rectifier-inverter. This motor should be designed generously, however, so as to enable it to meet its maximum demand of 2.55 per cent under the condition of considerably reduced voltage. On short-circuit of the rectifier d-c terminals, the power interchange becomes practically zero (since $E_1 = E_n = 0$).

The generator armature of the motor-generator set carries the triple frequency condenser current caused by the voltages $E_n$ and $E_r$ which, in the case of the problem, resulted in a current of 153 per cent of nominal d-c rectifier current. The voltages $E_n$ and $E_r$ were each 20 per cent at nominal load making a resultant of 28.2 per cent so that the single-phase rating of the generator is approximately 18 per cent of the nominal rating of the rectifier. It appears that about 20 per cent of auxiliary machine capacity (motor and generator) is needed to make this scheme of rectification and inversion successfully operative. Comparing the conventional polyphase a-c system with this one, the percentage kva of auxiliary apparatus such as synchronous condensers required by the former increases with the power transmitted over a given line and the distance while, in the latter, the percentage capacity of auxiliaries does not increase with these factors but decreases with the kva of generating capacity behind the rectifier-inverter.

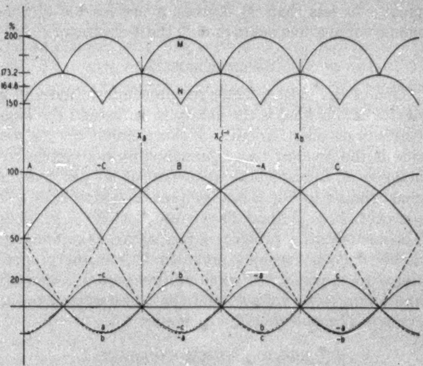

FIG. 7—DIRECT-CURRENT VOLTAGE FORMS

*A*, *B* and *C*—fundamental emf's after rectification
*a*, *b* and *c*—3rd harmonic emf's after rectification
*M*—ideal d-c voltage form
*N*—actual d-c voltage form (dotted components eliminated)

## VOLTAGE FORMS AND RATIOS

The wave form of the a-c voltage used in this apparatus is seen to be peaked sharply by the effect of the 3rd harmonic $E_n$, and somewhat distorted by the harmonic $E_r$. This form is advantageous to the rectifier in that the maximum strain occurs when the brushes are far removed from the segment tips and the rate of increase of voltage is moderate at the borders of the commutation period.

The normal form of the d-c voltage shows a constant value modified by convex ripples which have the form of a half wave of a 3rd harmonic. This form is common with other types of rectifier. If all the voltage values of the three sinusoidal fundamentals could be utilized, the d-c voltage would be represented by the curve *M* of Fig. 7 the values of which vary between 200 per cent and 173.2 per cent of a fundamental maximum. When all voltage values within 30 degrees of zero of each wave are sacrificed to a short-circuit or commutation period as indicated by the dotted parts of the fundamental rectified waves shown in the lower part of the figure, the d-c voltage *N* will vary between 173.2 per cent and 150 per cent, yielding an average value of 164.8 per cent. This figure may be taken as the normal d-c to a-c voltage ratio of the rectifier-inverter.

If the negative 3rd harmonic, in phase, is considered as included in each phase-voltage and the portions deleted by the commutation period shown dotted in Fig. 7 are ignored, it appears that no contribution to the d-c voltage is made by the harmonics. This relationship holds for the harmonic in any phase position with respect to the fundamental. For a commutation period greater or less than 60 degrees, a net residue of harmonic voltage does act to modify the d-c voltage.

## SHORT CIRCUITS

One of the most difficult requirements to meet in a device of this kind is the ability to withstand the high currents on short circuit. A short circuit on the d-c side is the severest test. Assuming an a-c system reactance at fundamental frequency of 20 per cent, a chart similar to Fig. 2 has been made, taking $I_d = 500$ per cent, $E_r = 5$ times 20 per cent, and $E_1 = E_n = 0$. The commutation problem is here solved as completely as for nominal currents provided $E_r$ remains proportional to the load, the commutation period is entered and left at zero voltage, and the transformer current curve has become roughly triangular.

## CHANGE OF SYSTEM CONSTANT *L*

Since the inductance corresponding to total a-c system reactance is a factor determining the 3rd harmonic commutating voltage $E_r$, the change of this constant caused by switching lines, generators or other machines might cause some concern about the ability of the rectifier to commutate properly after such change. The case of a generating plant with four similar units was assumed. Typical values for the transient reactances per phase of the generators and of the leakage reactances of the transformers were used.[6,7] It was found that $E_r$ varies but 10 per cent between the cases of one and of four generators in operation. Experience with the experimental apparatus has shown that a 10 per cent error in the value of $E_r$ produces slight and harmless changes in the forms of the transits.

## APPLICATION TO D-C TRANSMISSION

In setting up a d-c transmission system using this rectifier-inverter, one of the units operating as a rectifier would be supplied through its bank of raising transformers from an a-c system *A*. The d-c line including the harmonic-generator field would be grounded. The other d-c terminal would lead to the single-wire transmission line. Two commutators each operating between ground and line, but of opposite polarity, would be preferable. This would result in a two-wire transmission and eliminate the ground as a conductor. The receiving end of the d-c line would have a similar complement of commutators acting as inverters and feeding into the a-c system *B*. On account of the perfect reversibility of the transforming means, the flow of power might occur in either direction and would be under the control of the relative voltage levels of the two systems. These levels could be modified arbitrarily by the transformer-ratio switches. If two conductors of a typical three-phase line were thus employed, the third and nominally unused conductor would be the full equivalent of a spare circuit. The frequencies maintained by systems *A* and *B* would be of no concern in the operation of this system, there would be no problem of stability, nor would there be any closely defined power limit.

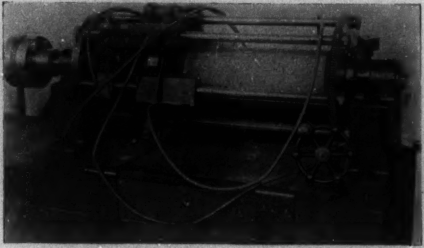

FIG. 8—RECTIFIER-INVERTER FOR THREE-PHASE D-C OPERATION

These rectifier-inverter units seem well adapted to parallel operation since all the commutators function in step. The load distribution as between units would be largely controlled by the transformer leakage reactances. A d-c network might well be established to which certain rectifying units would deliver power and from which other inverting units would take power to be transformed into polyphase a-c power for a local system which, however, should supply its own excitation and fix its own frequency.

## USE AS A FREQUENCY-CHANGER

Two commutators of this type, driven by separate synchronous motors, might serve as a frequency-changing tie between, say, a 60- and a 25-cycle system. The capital cost of such a tie should be much smaller than that of the frequency-changing units now in use in which the power flow must undergo two electromechanical transformations.

## HYPOTHETICAL DESIGN

In order to provide practical checks on the possibilities and limitations of this apparatus as applied to rectification and inversion for the purpose of d-c transmission, an actual design problem has been worked out in parallel with the theory evolved. The assumption has been made that each element of the rectifier would be able to withstand what will no doubt appear to the reader as an impossibly high voltage as but three elements were assumed. The voltage per element may be reduced by going to six, twelve or more elements in series, with a sacrifice in simplicity. The conduct of this design will not be described in detail but the assumptions, data and results are listed below. The size of the equipment was chosen to correspond approximately to the safe capacity of a present-day 250-mile, 220-kv, three-phase line. Two equipments are supposed to operate in series to supply a two-conductor d-c circuit. The results obtained refer to one of these equipments.

*Data Assumed*

D-c rating per rectifier = 375 amp, 144.5 kv, 54,150 kw

D-c rating of pair in series = 375 amp, 289 kv, 108,300 kw

A-c system 60 cycle reactance = 20 per cent ($L$ = 0.086 h)

A-c voltage at rectifier at zero load = 100 per cent

A-c voltage at rectifier on short-circuit = 0

Direct current on short circuit = 500 per cent

Commutation period = 60 deg (fundamental)

100 per cent voltage = $E$ (max.) = 87.7 kv

100 per cent current = 375 amp

*Results Derived*

Normal ratio total d-c volts/$E_1$ (max.) = 1.648

Capacity per condenser = 4.675 $\mu$f at 114 kv (max.)

Total rating based on effective values = 48,700 kva

Rating of transformers

$$\left.\begin{array}{l}\text{Voltages} = 13.2\text{ kv}/62\text{ kv} \\ \text{Current} = 375\text{ amp (ht)}\end{array}\right\} \begin{array}{l}\text{kva} = 23{,}250 \\ (69{,}750\text{ kva, total})\end{array}$$

Ratings of motor-generator set

Motor = 956 kw at unity pf = 1.77 per cent

Generator voltage = 28.2 per cent = 17,500 v

Current = 3 × $I_{c3}$ = 575 amp

Kva = 10,050 = 18.5 per cent

Table I gives the variations of $E_1$, $E_r$, $E_n$ and power transfer in the harmonic motor-generator set for loads varying from zero to 500 per cent (short-circuit) for the case of rectification. Table II shows the variations of the same quantities for the case of inversion on the assumption that $E_1$ again varies from 100 per cent at zero load to zero on short circuit.

TABLE I—POWER TRANSFERS—RECTIFICATION

| % Load | % $E_1$ | $E_r$(%) | $E_n$(%) | Power transfer in kw |
|---|---|---|---|---|
| 0 | 100 | 0 | 25 | 0 |
| 25 | 95 | 5 | 23.75 | − 287 |
| 50 | 90 | 10 | 22.5 | − 543 |
| 100 | 80 | 20 | 20 | − 956 (nom. load) |
| 250 | 50 | 50 | 12.5 | − 1485 |
| 400 | 20 | 80 | 5 | − 956 |
| 500 | 0 | 100 | 0 | 0 (short circuit) |

TABLE II—POWER TRANSFERS—INVERSION

| % Load | % $E_1$ | $E_r$(%) | $E_n$(%) | Power transfer in kw |
|---|---|---|---|---|
| 0 | 100 | 0 | 25 | 0 |
| 25 | 95 | − 5 | 23.75 | + 287 |
| 50 | 90 | − 10 | 22.5 | + 543 |
| 100 | 80 | − 20 | 20 | + 956 (nom. load) |
| 250 | 50 | − 50 | 12.5 | +1485 |
| 400 | 20 | − 80 | 5 | + 956 |
| 500 | 0 | −100 | 0 | 0 (short-circuit) |

## CONSTRUCTION OF EXPERIMENTAL MACHINE

An experimental rectifier-inverter was built and tested in the laboratory at Lehigh University. This apparatus, shown in Fig. 8, comprises four canvas-base Formica disks, 6.5 inches in diameter and 0.75 inches wide, carrying the contacting segments. The twin brush sets mounted on fiber blocks may be shifted angularly by a worm gear. The brushes are of laminated copper, providing a contact area 0.75 in. by 0.5 in. Two extra brushes in parallel riding on each of the two terminal disks serve as connections to the d-c lines. The rectifier is run by a two-pole self-synchronizing three-phase motor. The segment group measures eight inches in axial length. The brush rigging is built to accommodate additional segment disks for six-phase operation.

## AUXILIARY APPARATUS

A special General Electric harmonic motor-generator set was used to supply the three-phase power. The fundamental frequency generator served to operate the rectifier motor and to supply power to the transformers as in Fig. 5. One phase of the 3rd harmonic machine of this set injected the voltage $E_r$ into the neutral. The field of this machine was connected in series with the d-c circuit of the rectifier and was adjusted by an inductive shunt. The harmonic voltage $E_n$ was introduced into the neutral by a second 180-cycle generator connected to the main set. The field of this was excited in shunt from the d-c rectifier voltage when this was not too high. Equal reactances were connected into each of the a-c supply lines and adjusted for a drop of 20 per cent at nominal load (5 amp).

A 250-volt and a 1,500-volt motor-driven d-c generator were used at different times as a d-c system for the purpose of loading. Sudden changes of d-c system voltage for the purpose of causing transient reversal from rectification to inversion were produced by switching resistance in and out of the d-c generator field. A high steadying reactance in the d-c circuit made possible a direct current practically free of ripples.

## Experimental Results

The oscillograms of Fig. 9 show the operation as a *rectifier* with a d-c voltage of about 150. The symbols naming the various traces have the meaning attached to them in the earlier parts of the paper. It will be interesting to compare the wave forms of this figure with those predetermined for different conditions shown in Fig. 2. It will be noted that the d-c voltage, the transformer current and the rectifier current are in phase.

Fig. 10 shows similarly the operation as an *inverter*. The a-c voltage and current are now in phase opposition. These curves demonstrate the manner in which the a-c system current-form results from the combination of the steady current from the inverter and the condenser current.

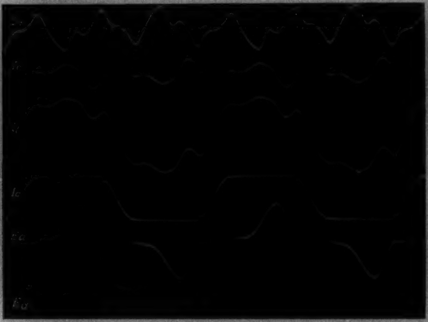

Fig. 9—Oscillograms of Rectifier Operation With High Steadying Reactance in the D-C Circuit

$I_n$—Neutral current
$I_c$—Condenser current
$I_t$—Transformer current
$I_a$—Rectifier (a-c) current
$E_a$—Rectifier a-c voltage
$E_d$—D-c voltage

Fig. 11 shows zero load operation. The surges in the condenser current indicate discharges due to imperfect voltage neutralization at the beginning of the short-circuit period.

The oscillograms shown do not represent operation as satisfactory as is obtainable at larger currents; they were selected as best typical of Figs. 2 and 3. A ninth harmonic of voltage, probably due to the reactions in the auxiliary machines, appears on heavier loads which modifies the forms of $I_t$ and $I_c$ considerably but produces no change in the quality of the transits (see Fig. 12 for heavier loads).

## Automatic Adjustment of $E_r$ and $E_n$

In order to make a check on the perfection of the automatic adjustments of the harmonic voltages $E_r$ and $E_n$ with load changes, it was decided to cause a transient load change. Two values of field excitation for the d-c system machine were found, one resulting in nominal direct current inverting and the other giving the same current rectifying. By the throw of a switch the rectifier could suddenly be thrown from one operating condition into the other. Since the transient associated with field decay giving a change from inversion to rectification practically was complete within 2 seconds, it was selected for the oscillograms of Fig. 12. It will be noted that $E_n$ decreases with the a-c system voltage, $E_r$ passes through zero and reverses in phase at the cross-over point, $I_a$ undergoes similar changes, the direct current and the three-phase watts reverse at the same point. This performance seems promising since it was obtained by means of auxiliary apparatus not especially designed for the purpose. No arbitrary adjustments of any kind were possible during the passing of this transient and the commutation was perfectly black during the period.

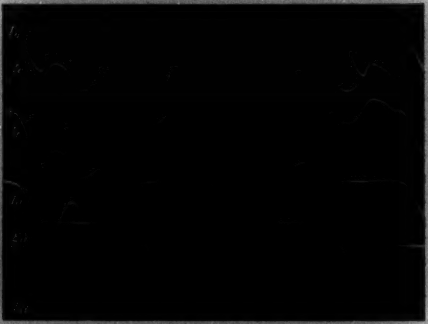

Fig. 10—Oscillograms of Inverter Operation with High Steadying Reactance in the D-C Circuit

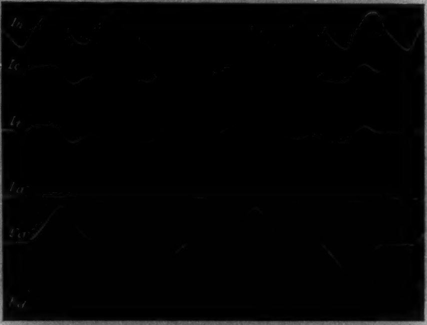

Fig. 11—Oscillograms of Zero-Load Operation

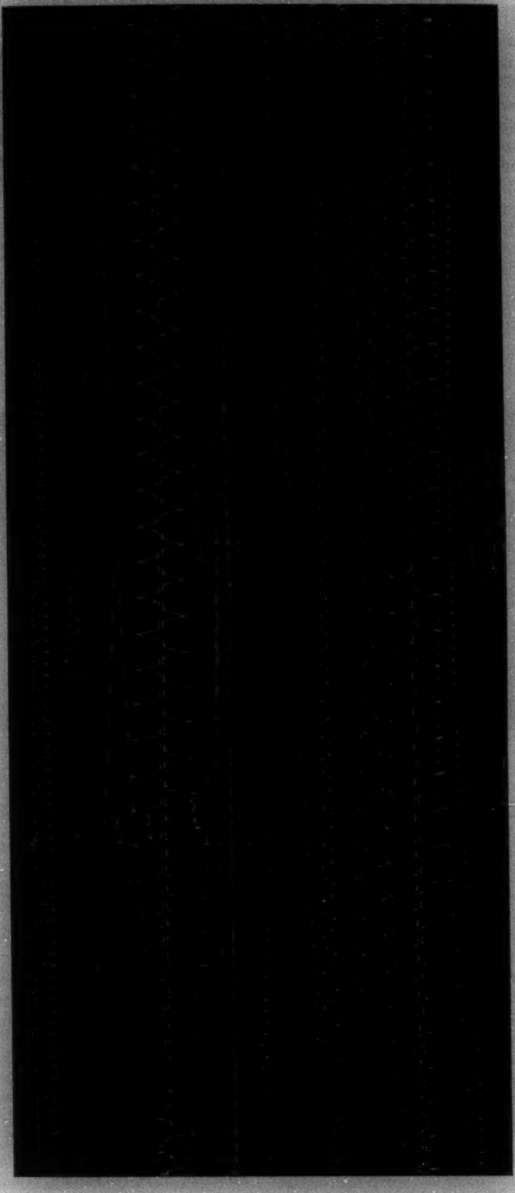

Fig. 12—Oscillograms of Transient Passage from Inversion to Rectification Operation

(All adjustments automatic)

### INVERTER WITHOUT A-C EXCITATION

The commutator operates without sparking when the a-c system is totally disconnected and, with the help of the transformers and condensers, generates polyphase voltages of non-sinusoidal wave form. Contrary to what was at first believed, the apparatus can supply not only power but also polyphase excitation to the a-c system as demonstrated by the following experiment.

The inverter was supplied with nominal d-c voltage. A balanced three-phase resistance load (5 amp nom.) was arranged to be thrown on suddenly. A highly reactive balanced three-phase load of 5 amp was similarly arranged. The transient of Fig. 13 occurred when the non-inductive load was disconnected and the inductive load thrown on. None but the automatic adjustments of $E_n$ and $E_r$ could occur during the period. The transits were satisfactory and the commutation absolutely sparkless. The excessive voltage amplitudes during the no-load period are due to the stored energy in the high d-c line reactance. A moderate reactance at this point will result in reasonable values of the a-c voltage.

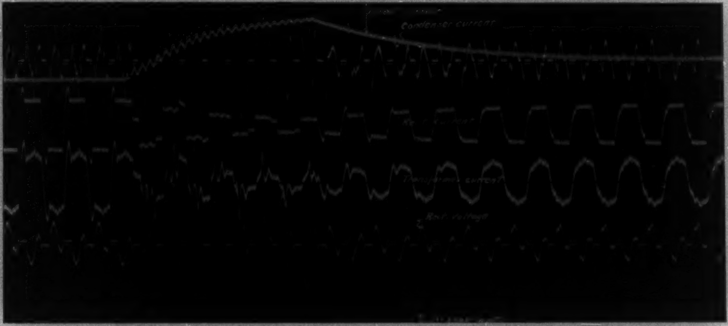

FIG. 13—INVERTER OPERATION WITHOUT A-C EXCITATION

Transient from three-phase resistance load to three-phase highly reactive load

The apparatus has been operated on currents up to 25 amp (the limit of receiving machine) without sparking and with observed transits of the same form as those shown in the oscillograms. The highest d-c voltage used on rectification and inversion was 1,500. At this voltage, the current passed was 2 amp (the limit of the receiving d-c machine). The commutation was again sparkless. The apparatus demonstrated its sturdiness in that considerable changes in $E_r$, $E_n$ or brush position could be made under load without causing sparking.

### SUMMARY

The following conclusions may be drawn as a result of this work:

1. A synchronously driven rectifier of the short-circuiting type can be made to be perfectly reversible so as to permit operation as an inverter.

2. Theoretically correct a-c voltage conditions to assure proper commutation and sparkless operation may be secured by the use of two odd harmonic voltage components ($E_n$ and $E_r$).

3. The two harmonic components $E_n$ and $E_r$ can be automatically varied so as to secure successful operation on transient load changes including that of d-c short circuit.

4. The apparatus designed for the above uses is capable of delivering both power and excitation to an unexcited polyphase system.

5. A rectifier-inverter of the kind described can take the place of moderate-voltage converting or frequency-changing equipment and promises to be of use in the solution of the problem of high-voltage d-c power transmission.

### LIMITATIONS

1. The rectifier-inverter described is a rotating machine.

2. The problems of rotor balance and of wear must find solution.

3. The practical voltage limits have not been determined.

4. When used in connection with high total a-c system reactance, a considerable kva capacity of auxiliary machinery and condensers is required.

### ACKNOWLEDGMENT

The author wishes to acknowledge the suggestions and encouragement given by the electrical engineering faculty of the Massachusetts Institute of Technology where this work was pursued as a doctor's thesis. He also expresses his appreciation of the important help of Professor N. S. Hibshman, of Lehigh University, in the conduct of the experimental work and the preparation

of the paper, and to Professor A. R. Miller for valuable assistance in taking and preparing oscillograms.

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## Discussion

**N. S. Hibshman:** Since the author's remarks on the subject of the application of the rectifier have been confined to the field of high-voltage transmission where system reactances are necessarily high, and the use of a static condenser as an aid to commutation has therefore been assumed, it may be pertinent to add that the condenser is not essential to the operation of the rectifier, but is rather to be considered as a means of relieving the duty of the quadrature third-harmonic voltage to whatever extent the economics of the particular case may dictate.

The maximum value of the quadrature third harmonic, or commutating voltage, is given by equation (2) in the paper. Assuming several values of system reactances and for each plotting the commutating voltage ($E_r$) amplitude in per cent of fundamental amplitude as a function of capacitance the graphs of Fig. 1 result. It then appears that satisfactory commutation may be had with any combination of capacitance and $E_r$ within the limits shown. It will be seen that in a low-reactance system such as would be associated with a low-voltage power rectifier, the condenser has little effect and may be eliminated without material effect on the required percentage of $E_r$. However, according to equation (3), it appears that the condenser component of harmonic current has an important influence on the value of the neutralizing harmonic voltage and that the elimination of the condenser will call for considerable increase in the amplitude of the generated $E_n$.

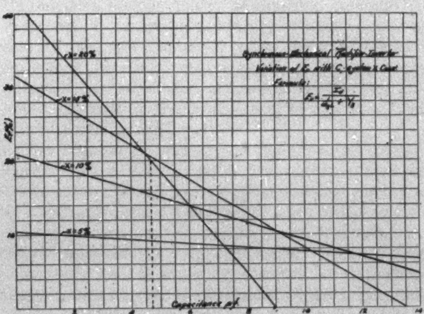

FIG. 1—COMMUTATING VOLTAGE, $E_r$, IN PER CENT OF FUNDAMENTAL PHASE VOLTAGE PLOTTED AGAINST CONDENSER CAPACITANCE FOR REPRESENTATIVE SYSTEM REACTANCES

The oscillograms in Fig. 2 were made while the rectifier operated without condensers, and show that the quality of commutation is unimpaired by the absence of the condenser when its function is supplanted by the proper increase in commutating and neutralizing voltages.

The oscillograms were made with the rectifier operating as part of a miniature three-phase system of 20 per cent reactance in which the nominal d-c load was 5 amperes. The experimental rectifier has delivered 25 amperes when operating on high reactance systems and as much as 75 amperes on low reactance systems. The latter current represents an average current density at the brush contacts of 200 amperes per square inch. At no time, however, has the capacity of the experimental rectifier been reached, the load limit having been set by the capacity of auxiliary equipment in all cases.

FIG. 2

*A*—Oscillogram of a-c voltage and current operating as an inverter without condenser

*B*—Oscillogram of d-c voltage and neutral current for inverter operation corresponding to *A*

*C*—Oscillogram of a-c voltage and current input—rectifier operation without condenser

*D*—Oscillogram of d-c voltage and neutral current—rectifier operation as in *C*

**H. E. Kent:** The oscillograms in the paper indicate the presence of considerable wave shape distortion on both the a-c and d-c side of the rectifier-inverter. This is of interest in its bearing on the coordination of power and communication systems from the standpoint of noise induction, since power system wave shape is an important factor in this problem.

In recent years there have been a number of cases of noise interference in telephone circuits where wave shape distortion caused by mercury arc rectifiers was involved. Experience has shown that in those situations involving wave shape distortion on the d-c load side of a rectifier selective devices such as resonant shunts offer a feasible method of reducing such distortion. However, where the a-c supply circuits to a rectifier are concerned in a case of interference, the problem is more difficult and no generally applicable solution has been found. The Joint Subcommittee on Development and Research of the N.E.L.A. and Bell System is actively working on this latter aspect of the wave shape distortion caused by mercury arc rectifiers.

In view of the difficulties which have been experienced in attempting to improve the wave shape of the a-c supply lines to rectifiers by the application of external equipment it would appear to be very desirable that consideration be given to wave shape during the development stage of these new types of rectifiers and inverters.

**J. J. Linebaugh:** Professor Seyfert has given an interesting analysis and description of a synchronous-mechanical rectifier-inverter, but it is evident that a great amount of work will be required to obtain a practical commercial unit even for fairly low voltages.

There are many difficult problems in the design of a mechanical rectifier commutator to take care of appreciable currents and the writer believes such a commutator is still to be developed. During the years 1924-27, the writer was actively connected with Mr. T. C. Lennox in an attempt to build such a commutator and, although after several trials a fairly successful commutator was produced, it still had serious limitations for large capacities.

It would be interesting to learn why standard graphite brushes were not used instead of the copper brushes with their short life and inclination to cut and wear the segments. The copper dust from such brushes is also very objectionable especially for high voltage commutators.

Did Professor Seyfert try to overload the sample commutator or raise the amperes to be commutated above 25 amperes?

**S. S. Seyfert:** Replying to the question of Mr. Linebaugh as to the highest currents and voltages that can be handled by this rectifier-inverter, the writer would recall Professor Hibshman's discussion; which stated that the largest direct current passed by the experimental apparatus was 75 amperes with an a-c system reactance of 5 per cent. This value was reached as the practical limit of the auxiliary machines' capacity for furnishing the harmonic voltage. The theoretical limit of current, apart from that imposed by the auxiliaries, is the brush contact area provided by the design. The voltage limit is determined by the arcover value or by the exactness of voltage neutralization that can be maintained.

Carbon brushes were at least temporarily abandoned for laminated copper because the lack of facilities prevented the securing of dynamic balance of the rotor. The metal brushes rode the rings perfectly in spite of considerable vibration. Under normal operation, no biting action at the segment tips was noted and the rotor was trued but once during the experiments, after a period of unusual abuse.

In response to Mr. Kent's suggestion that consideration be given to the harmonics in the a-c supply system, it may be said that, although the a-c wave form acting from line to neutral in the transformers is modified greatly by the insertion of the harmonics into the neutral connection, the voltage between lines still remains sinusoidal. In the connection shown by Fig. 5 of the paper, the 3rd harmonic components of current and multiples thereof such as the 9th, 15th, etc., must needs flow in the neutral connection to the generating source. This flow of the harmonics may be prevented or at least greatly reduced by locating the condensers $C_1$, $C_2$ and $C_3$ between lines and neutral immediately to the left of the harmonic generator $A_h$ without seriously impairing their effectiveness as an aid to commutation.

Although the apparatus was developed with the idea of applying it to the solution of the problem of high-voltage transmission, it would at present appear that the application attended with least practical difficulty would be that of rectification or inversion in connection with moderate voltage systems. When so applied, there should result a considerable reduction in capital investment and a large increase in efficiency since the estimated losses would be but slightly greater than the nominal losses in the transformers.

# Progress Report on Impulse Testing of Commercial Transformers[‡]

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and

V. M. MONTSINGER[†]
Fellow, A.I.E.E.

***Synopsis.****—The transformer subcommittee of the A.I.E.E. electrical machinery committee presents herewith a progress report covering its work to date on the impulse voltage testing of commercial electric power transformers. A tentative test procedure has been agreed upon, although complete agreement has not yet been reached on all details. It is hoped that this report will stimulate among members of the Institute discussion that will be helpful to the committee in completing a formal test code during the coming year.*

AT THE A.I.E.E. winter convention in January 1932, the electrical machinery committee of the Institute assigned to the transformer subcommittee the task of determining the feasibility of impulse voltage tests on commercial transformers and of making recommendations for such tests, if possible. Agreement has been reached on a tentative test procedure, although complete agreement has not yet been reached on all details.

One of the first questions considered was the possibility of detecting impulse voltage failures. Transformers in service show the effects of insulation failure only by their inability to deliver power and by the formation of power arcs within the windings. For this reason, the combination of normal frequency excitation with impulse tests was carefully considered, since with this arrangement service conditions are duplicated and a transformer withstanding a test of this kind reasonably might be expected to stand up in service. Considerable experience with such a method already had been obtained when the subcommittee undertook this study, and the results of this experience appeared favorable; the subcommittee therefore devoted its efforts to the development of a practical test procedure along this line.

The purpose of making impulse tests on a transformer is to give a reasonable demonstration that the transformer has met the specification requirements as to impulse strength. The low frequency dielectric tests that have been used in the past cannot demonstrate this because the low frequency test voltage is of lower magnitude and is uniformly distributed throughout the winding, whereas the lightning voltage is generally of much higher magnitude and may depart radically from a uniform distribution. Impulse tests therefore will give a more adequate demonstration of the sufficiency of the insulation strength of transformers for service conditions.

## EQUIPMENT REQUIRED FOR TESTING

Impulse testing equipment (generator, discharge circuit, cathode ray oscillograph, and voltage divider) shall consist of only such parts and circuits as can be analyzed readily regarding the constants which have an appreciable effect upon the shape and amplitude of the voltage wave applied to the transformer under test. Such factors as the capacitance and inductance of the transformer under test, length of circuit from impulse generator to transformer, length of cable from divider to cathode ray oscillograph, length of main discharge circuit, as well as electromagnetic and electrostatic interference effects all must be taken into consideration. Testing technique and operation of the testing equipment should be that best suited for the purpose.

The equipment, in addition to that required for the producing and recording the waves, will consist generally of a source of power for exciting the transformer under test, means for synchronizing the impulse wave with the crest of the alternating voltage wave, a standard point gap, and means for limiting the power-follow across the gap. A technique of cathode ray oscillograph measurement should be developed for each test equipment so that the accuracy of the oscillograph and its potentiometer with respect to both time and voltage can be demonstrated.

The equipment should be located as closely together as possible. Nevertheless, it is necessary to provide sufficient space between all parts of the equipment so that there is no interference, and to provide for practical considerations. With this in mind, and to permit reasonable accuracy, it is recommended that the transformer terminals, coordinating or test gaps, and measuring equipment be within a range of less than 150 circuit feet.

## METHODS OF APPLYING TESTS

Constants of the surge generator should be adjusted so that the specified wave shape is obtained with the transformer connected. After the proper initial adjustments for the transformer under test are completed, changes in the test voltage can be made by varying the voltage applied to the surge generator, without requiring additional demonstration in regard to wave

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[*] Westinghouse Elec. & Mfg. Co., Sharon, Pa.

[†] General Elec. Co., Pittsfield, Mass.

[‡] Sponsored by the transformer subcommittee of the A.I.E.E.—H. V. Putnam, *chairman;* G. M. Armbrust, E. S. Bundy, J. E. Clem, Basil Lanphier, H. C. Louis, A. C. Montieth, V. M. Montsinger, L. C. Nichols, E. D. Treanor, and F. J. Vogel.

*Presented at the A.I.E.E. Winter Convention, New York, N. Y., January 23-27, 1933.*

shape. Should the voltage applied to the transformer be changed by changing the constants of the circuit, it will be necessary, of course, to demonstrate the wave shape for the changed conditions.

The impulse wave should be applied with the transformer excited and with the wave synchronized at or within 30° of the crest of the excitation voltage. The two waves should be of opposite polarity at the time of synchronization, as this provides the severest test of the windings.

The test should be made on one terminal at a time. This simplifies test procedure, and generally will satisfy all requirements for a rigid test. Where series transformers for regulating purposes or other similar equipment require special protective devices, these should be in the circuit during the tests. During each test all bushings on windings not being tested will be either grounded or protected by appropriate means.

### TYPE OF WAVE TO BE APPLIED

The full wave will be satisfactory if it has a nominal front of from ½ to 2½ μsec, and a tail reaching half the crest voltage in from 40 to 50 μsec from the point on the front of the wave at which the voltage is 10 per cent of the crest voltage. The nominal front of the wave can be determined by measuring the time between points on the front at which the voltage is, respectively, 10 and 90 per cent of the crest value; this time divided by 0.8 will define the front of the wave. If there are oscillations on the front of the wave, the 10- and 90-per cent points should be determined from the average smooth wave front sketched in over the oscillations. The wave should be as smooth as possible because oscillations have the effect of increasing the stress on the winding under test. The wave shape should be recorded by the cathode ray oscillograph.

### TESTS TO BE APPLIED

In all tests the transformer tank will be grounded directly and test gaps, where they are used, will be connected directly to the same ground. Each terminal of the transformer to be tested should be tested with waves of positive polarity having respectively:

1. A voltage not more than 10 per cent less than the minimum impulse voltage permitted by the specified test gap directly connected to ground.
2. A voltage just sufficient to flashover the specified test gap directly connected to ground.
3. A crest voltage at least 10 per cent greater than the minimum flashover voltage of the test gap directly connected to ground.
4. A voltage of sufficient magnitude to flashover the bushing.
5. A voltage as great as that specified in No. 3 or 4, but with means for maintaining the excitation voltage across all parts of the winding. The purpose of this requirement is to prevent short-circuiting the windings through the power follow over the gap or bushing immediately after the impulse, which would cause the dynamic voltage to collapse and thus prevent the detection of an internal failure.

It is recognized that these tests do not make any allowance for the effects of variations in humidity and relative air density, and may not provide tests of the desired severity. However, the transformer subcommittee is giving consideration to these matters.

The transformer bushing and test gap shall have a minimum flashover voltage at least 10 per cent greater than the minimum flashover voltage of the proposed standard A.I.E.E. coordination gaps.[1] To obtain this, test gaps as indicated in Table I will be used.

### THE DETECTION OF FAILURES

Because of the nature of impulse voltage failures, one of the most important matters is the detection of failure. There are a number of positive indications of insulation failure. Some of these are: noise within the transformer; presence of smoke; excessive current or drop in voltage in the excitation circuit; failure of the gap or bushing to flashover when actually a sufficient surge voltage is applied; presence of oscillations or other variations from the expected wave shape as indicated by cathode ray oscillograms. These are positive indications of failure and will satisfy all practical requirements.

TABLE I—TEST GAPS RECOMMENDED FOR IMPULSE TESTING OF TRANSFORMERS

| Circuit voltage class, Kv | Tentative standard coordination gap, In. | Test gaps, In. |
|---|---|---|
| 2.3- 4.3 Y | 2* | 2¼ |
| 4.6- 8.67 Y | 3* | 3³/⁸ |
| 6.9-13.8 or 15 Y or Δ | 4¼ | 4¾ |
| 23 | 6¼ | 7 |
| 34.5 | 9¼ | 10¼ |
| 46 | 12¼ | 13½ |
| 69 | 18¾ | 20½ |
| 92 | 25 | 27½ |
| 115 | 31½ | 34¾ |
| 138 | 38¼ | 42 |
| 161 | 44½ | 49 |
| 196 | 54½ | 60 |
| 230 | 64 | 70½ |

*Recommended by the transformer subcommittee on Nov. 18, 1932.

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## Discussion

For discussion of this paper see page 440.

# Factors Influencing the Insulation Coordination of Transformers

BY F. J. VOGEL*

Associate, A.I.E.E.

## INTRODUCTION

IN the early days of the electrical industry, surges were relatively mysterious as to their origin, magnitude and behavior. The ordinary factory tests now required by the A.I.E.E. rules were the reflection of experience and judgment rather than the analysis which has been made possible in the last few years. From experience, it was found on the one hand that it was necessary to increase the insulation of some parts of the transformers far above the requirements of the A.I.E.E. rules (*i. e.*, turn and coil insulation, bushings) and, on the other hand, to limit the voltages transmitted to the transformer from the line, by the specification of line insulation and protective gaps.[1] In the meanwhile, progress has been made in the laboratory study of the surge characteristics of the insulators, gaps, and insulation structures commonly used in transformers.[2] This paper presents data from these insulation studies and shows the relationships between the present coordination standards and the strength of transformer insulation. The results of tests of insulation under oil are reported, the strength of the various voltage ratings of transformers estimated and these in turn compared to the flashover values of line insulation and gaps.

## SURGE STRENGTH OF INSULATIONS UNDER OIL

The heart of the insulation of a transformer, as determined by the present A.I.E.E. rules, is in the insulation between the high-voltage and low-voltage windings, commonly known to the designer as major insulation. It is desired to keep these insulation clearances as small as possible to obtain low reactance, low losses, and the greatest economy in materials. The conventional means of obtaining such a result is in the use of tubes and angle rings in the core type transformer, and in the use of sheets and angles interleaved in the shell type transformer. Such constructions are shown in Figs. 1 and 2. Accordingly, models using these constructions were made and given both 60-cycle and surge tests, for the purpose of obtaining data on the strength of major insulation.

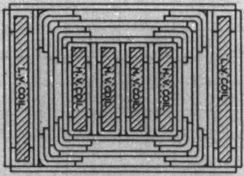

FIG. 1—VIEW OF SHELL TYPE TRANSFORMER INSULATION IN IRON OPENING

High-voltage and low-voltage coils are shown shaded

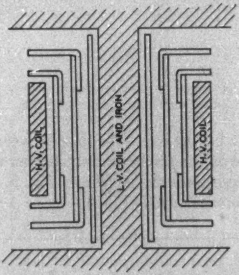

FIG. 2—VIEW OF CORE TYPE TRANSFORMER INSULATION MODEL

The low-voltage coil and iron are represented as one piece

It should clearly be understood that the results obtained apply only to the major insulation and do not represent the insulation strengths of complete transformers unless the insulation between turns and coils has been so made that even under the conditions of surge tests the major insulation is the weakest part of the entire structure.

The shell type models were first given 60-cycle tests to breakdown voltage. The results of these tests are as given in Table I. The procedure of testing was to hold the voltage 60 seconds, to allow 5 minutes rest and then to increase the voltage to the next step.

TABLE I—TESTS ON SHELL TYPE INSULATION MODELS
60 CYCLE—70 DEG C OIL

| Model | Voltage held 1 min—kv rms | Voltage at failure—kv rms |
|---|---|---|
| 15 | 280 | 290 |
| 16 | 300 | 310 |
| 17 | 290 | 300 |
| 18 | 270 | 280 |
| 20 | 260 | 270 |
|  | 280 | 290 |
| Average | 280 | 290 |

Similar models were tested to breakdown with positive surges at both Trafford and Sharon. The waves used were approximately 1½ μsec front and 40 μsec from the crest to half value. The results of these tests are plotted in Fig. 3. The comparison between these results and the 60-cycle tests (approx. impulse ratio) is shown in Fig. 4.

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*Transformer Engineering Department, Sharon Works, Westinghouse Electric & Mfg. Co.

1. For references see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

The core type models were likewise tested at 60 cycles to breakdown, with results as given in Table II.

TABLE II—TESTS ON CORE TYPE INSULATION MODELS 60 CYCLE—70 DEG C OIL

| Model | Voltage held 1 min—kv rms | Voltage at failure—kv rms |
|---|---|---|
| 3 | 300 | 310 |
| 4 | 270 | 280 |
| 7 | 300 | 310 |
| 8 | 320 | 330 |
| 9 | 280 | 290 |
| 10 | 310 | 320 |
| 11 | 300 | 310 |
| 12 | 320 | 330 |
| Average | 300 | 310 |

Surge tests on the core type models were made similarly to those on the shell type transformer models. The results of these tests are shown in Fig. 5, and the approximate impulse ratio in Fig. 6.

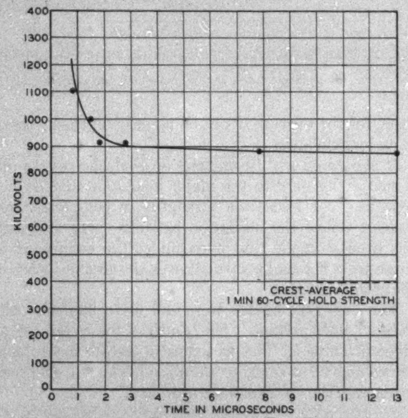

FIG. 3—TIME LAG CURVE OF SHELL TYPE TRANSFORMER INSULATION MODEL USING 1½-40 POSITIVE WAVE

It may be objected that these are not representative of all types of major insulation. These tests represent conditions where the dielectric field is formed between metal surfaces with square corners. The highest puncture voltages for a given distance have been obtained with flat sheets, in which case the formation of corona on the surface appears to result in a more uniform distribution of dielectric stress through the sheet. A comparison of the 60-cycle and surge strength for such conditions has been made. The barrier consisted of two ⅛-in. fullerboard sheets and two ⅜-in. oil ducts, as shown in Fig. 7. The extension of the barrier beyond the electrode was such as to produce puncture. The results of this test are given below:

| Max. 60-cycle hold strength 60 sec test | | Surge strength | | Impulse ratio |
|---|---|---|---|---|
| Rms | Crest | Voltage | Time lag | |
| 156 kv | 221 kv | 485 kv | 4.5 μsec | 2.2 |
| | | 450 kv | 5.5 μsec | 2.04 |

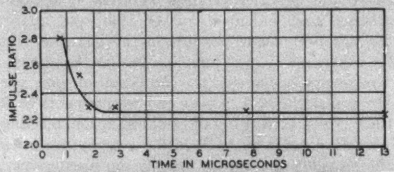

FIG. 4—IMPULSE RATIO CURVE OF SHELL TYPE TRANSFORMER INSULATION FOR 1½-40 POSITIVE WAVE

Indications in these tests were that the time lag curve was quite flat as even with increased voltage settings of the surge generator, no appreciable increase in breakdown voltage was obtained.

Similar tests with negative surges have been made. To accelerate the work, barriers similar to Fig. 8 were made, which simulate the conditions of interleaved insulation in the models. The average 60-cycle breakdown was found to be 345-kv rms or 490-kv crest.

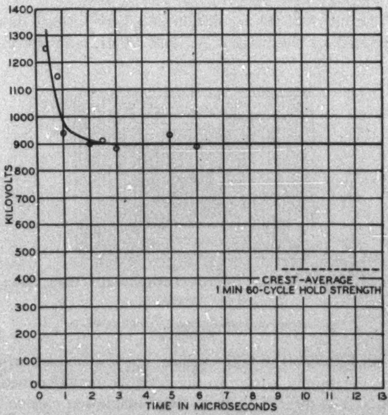

FIG. 5—TIME LAG CURVE OF CORE TYPE TRANSFORMER INSULATION MODEL USING 1½-40 POSITIVE WAVE

Positive time lag data are shown in Fig. 9, along with the results for the tests with negative waves. The average time lag curve of the major insulation of transformers, whether positive or negative, is therefore seen to be nearly the same and to be flat down to at least two or three microseconds.

To sum up these tests, it appears that the impulse ratio of transformer major insulation for time lags of the order of 2 microseconds or longer is approximately 2.2. These conclusions have been checked by tests of complete transformers and windings, where adequate winding strength, as in surge proof transformers,[3] was obtained.

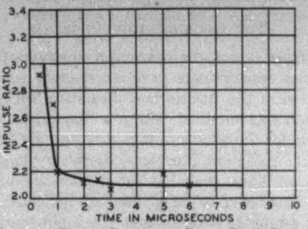

FIG. 6—IMPULSE RATIO CURVE OF CORE TYPE TRANSFORMER INSULATION FOR 1½-40 POSITIVE WAVE

## COMPARISON OF SURGE STRENGTHS OF INSULATORS, GAPS, BUSHINGS AND TRANSFORMER MAJOR INSULATION

In recent articles,[2] the strength of insulators and gaps has been published, and it is now possible to compare these against transformer insulation strength. This is best done by the use of time-lag curves. Accordingly typical time-lag curves of the 66-, 132- and 220-kv classes are shown in Fig. 10. In these curves, the standard conditions of air density and humidity of 25 deg C, 760 mm barometer and 6.5 grains of water vapor per cu ft of air are assumed. Further, in estimating the surge strength of the transformer insulation, the factor of 2.2 times the standard test voltage has been used which assumes the same factor of safety in the surge test for the major insulation as for the 60-cycle test. Since the factor of safety on test is unknown for different manufacturers, this makes the assumption that test or guarantee is not within closer limits for surge strength than for the 60-cycle breakdown strength.

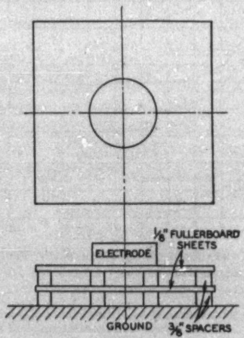

FIG. 7—ARRANGEMENT OF ELECTRODE AND INSULATION TO DETERMINE MAXIMUM PUNCTURE STRENGTH OF FULLERBOARD AND OIL DUCTS

Total thickness of fullerboard and ducts is 1 inch

For purposes of analysis, it is suggested that the 230-kv insulation class be chosen. From the curves, Fig. 10, the possible relationship between the service coordination gap, test gap or bushing, the previous standard of line insulation and the transformer insulation can be seen.

First, curve *C* shows the position of the line insulation with regard to the transformer insulation. This is of interest for two reasons. One is that it shows that coordination at short time lags might not be obtained with the recommended line insulation if the transformer were built just to meet the prescribed A.I.E.E. high-voltage winding tests. Another fact disclosed is that if the bushing is in excess of the line insulation, the margin between the bushing and transformer insulation may be greatly reduced.

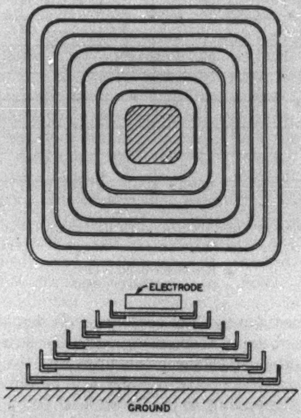

FIG. 8—ARRANGEMENT OF ELECTRODES AND INTERLEAVED INSULATION FOR CHECKING RESULTS OF MODEL TESTS AND FOR THE INVESTIGATION OF NEGATIVE SURGES

Next curve *A* shows the position of the coordinating gap relative to the transformer insulation. It is readily seen that ample margin will be obtained except at extremely short time lags, and since the time lag curve for transformer insulation also turns up, a margin is obtained.

The position of a proposed minimum bushing level is next shown as curve *B*. Several advantages of this level can be cited. First, it is desirable to keep this level as low as possible to provide a maximum margin between the insulation strength and the bushing flashover. Second, a sufficient margin above the coordinating gap is necessary to prevent bushing flashover in service. A minimum margin of 10 per cent probably satisfies both requirements to the best advantage. It should be particularly observed that protection to the extent of the coordinating gap cannot be obtained with the bushing, but the greatest degree possible will be obtained by keeping the bushing to the lowest level.

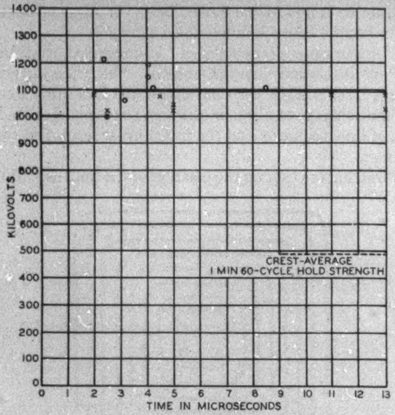

FIG. 9—SURGE VOLTAGE STRENGTH OF INTERLEAVED BARRIER FOR BOTH POSITIVE AND NEGATIVE WAVES

*x* Results for positive waves
*o* Results for negative waves

It is to be noted that the above relationships are for standard air density, humidity and positive waves. From inspection of the time lag curves, it will be seen that the shorter time lags are the critical ones. From inspection of the data furnished by Mr. F. D. Fielder, on density and humidity effects on gaps,[2] it is not believed that density or humidity conditions above the standard will appreciably affect the voltages at these short time lags. They will, however, be of importance for the longer time lags but here the margin of strength for the insulation is much greater.

Tests have been made with negative waves and they indicate little increase in voltage for short time lags compared to positive waves. There is however some increase in the voltage for long time lags due to change in polarity. Complete data of the effect of humidity on negative waves is not yet available. Nevertheless it is important that the effect of negative waves be considered. One reason for this is the fact that the highest lightning surges on lines have generally been found to be negative.[4]

An estimated curve of the relationships existing between the standard point gap and insulation for negative waves is shown on curve 11, for the 230-kv class. This is of interest in indicating still further the desirability of keeping the bushing characteristics at the lowest level.

## THE COORDINATION PROBLEM

Originally it was the opinion of engineers generally that since transformers gave satisfactory service, coordination of the transformer insulation with the line insulation was obtained. Surge voltage data were not available for the effects of humidity and air density on the line insulators, nor was there any appreciable amount of data available for insulations under oil. Service experience is not a thorough indicator of surge voltage strength, because first the number of strokes close enough to the station to result in the highest stresses possible is small, and second, even if close, the electrical constants of the transformer and substation may greatly modify and reduce them. It is of interest, therefore, (see Fig. 10) to note that with major insulation designed just to meet the requirements of the standard A.I.E.E. tests, coordination with the line insulators would have been obtained in the higher voltage classes except at very short time lags. The margin

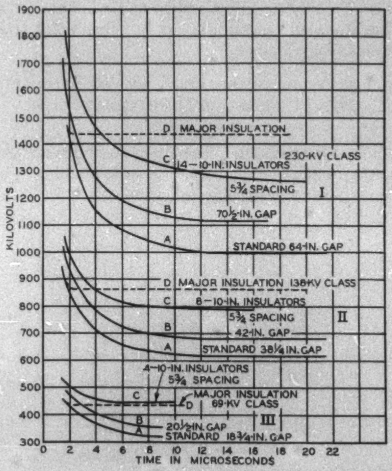

FIG. 10—COMPARISON OF POSITIVE WAVE TIME LAG CURVES FOR TRANSFORMER INSULATION WITH LINE INSULATION AND STANDARD GAPS

Group I is for 230-kv class, Group II is for 138-kv class and Group III is for 69-kv class. *A* for all classes is the present standard coordinating gap time-lag curve for the voltage class. *B* is the curve for the proposed gap for testing purposes and is a proposed bushing level. *C* is the curve for the line insulation formerly proposed for coordinating purposes. *D* is the minimum possible curve for the major insulation level based on the standard A.I.E.E. tests from the high-voltage winding to the low-voltage winding and ground of coordination diminishes in the lower voltage classes, disappearing entirely at the 69-kv class.

The point gaps more recently proposed show a logical agreement between the major insulation strength of transformers and the requirements dictated by experience. For example, the gap spacings used are in agreement with experience in furnishing comparatively longer spacings for the lower voltages, and are also logical in furnishing a simple relationship between the full wave values and the voltage class of the insulation as shown in Fig. 12.

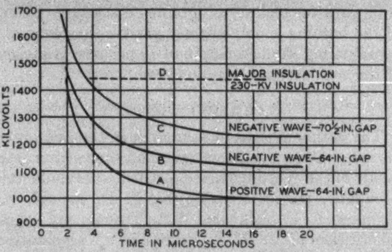

Fig. 11—Comparison of Positive and Negative Wave Time Lag Curves for Gaps and Transformer Insulation for the 230-Kv Class

*A* is the time-lag curve for a positive wave, the standard 64-in. gap and corrected to standard atmospheric conditions. *B* is the time-lag curve for a negative wave and the standard 64-in. gap, not corrected to standard atmospheric conditions. *C* is the curve for a negative wave for a 70½-in. gap proposed as a test standard and bushing level. *D* is the transformer insulation level

The surge strength of the major insulation and the gaps approach each other closest at a time lag of about 2 microseconds, due to the difference in the shape of their time lag characteristics. In determining whether major insulation is properly coordinated, it is necessary therefore to examine the conditions at the 2-microsecond point and make certain that at this point a margin does exist. Hence it is of interest to make an investigation of this sort in the several voltage classes to determine if major insulation designed to meet the requirements of the standard A.I.E.E. tests would be coordinated with the standard gaps at the 2-microsecond point. The results of such an investigation are presented in Table III.

In this table an effort has been made to arrive at logical values for the surge voltage requirements of the major insulation for the different voltage classes. It shows that in voltage classes 34.5 kv and above, the requirement that coordination be obtained at the 2-microsecond point will determine the necessary surge voltage strength of the major insulation, and that these surge voltage strengths so obtained, when translated into corresponding 60-cycle tests, give values almost exactly in agreement with the present standard A.I.E.E. tests. In the lower voltage classes, however, this requirement would dictate surge voltage strengths less than would be required to meet the surge tests proposed by the Transformer Subcommittee, so that in these lower voltage classes the proposed surge tests would dictate the necessary surge voltage strengths of the major insulation. These strengths translated into corresponding 60-cycle tests indicate that the present A.I.E.E. tests must appreciably be increased in these lower voltage classes.

Particular attention should be given to Fig. 10, in that the characteristics of the various time lag curves vary so radically. In the coordination work so far accomplished, characteristics such as obtained with the point gap or insulator strings only have been considered. The possibility of coordinating with a gap having impulse characteristics of similar shape to transformer insulation is an alternative. Such a gap might be a sphere gap. With the use of such a gap, a uniform factor of safety would be possible between transformer major insulation and the gap, instead of the variation now experienced between short and long time lags. An example of the results to be expected from such an arrangement is indicated as follows:

TABLE III

| Voltage class | Coordinating gap | Full wave (1½—40) standard gap | 2 microsecond strength standard gap | Major insulation transf. surge strength requirements (B) | 60-cycle (C) test req'd by surge strength | Present 60-cycle test |
|---|---|---|---|---|---|---|
| 2,300— 4,330 | 2 (A) | 55 | 55 | 1.21 × 55 = 67 | 21.6 (D) | 10 |
| 4,600— 8,670 | 3 (A) | 75 | 80 | 1.21 × 75 = 91 | 29.2 (D) | 18.4 |
| 6,900—13,800 | 4¼ | 95 | 105 | 1.21 × 95 = 115 | 37 (D) | 28.6 |
| 23,000 | 6¼ | 125 | 150 | 1.21 × 125 = 151 | 48.5 | 47 |
| 34,500 | 9¼ | 175 | 215 | 2 μsec value = 215 | 69.3 | 70 |
| 46,000 | 12¼ | 225 | 285 | 285 | 91.5 | 93 |
| 69,000 | 18¾ | 325 | 425 | 425 | 137 | 139 |
| 92,000 | 25 | 425 | 570 | 570 | 183 | 185 |
| 115,000 | 31½ | 525 | 715 | 715 | 230 | 231 |
| 138,000 | 38¼ | 625 | 860 | 860 | 276 | 277 |
| 161,000 | 44½ | 725 | 1,000 | 1,000 | 322 | 323 |
| 230,000 | 64 | 1,020 | 1,440 | 1,440 | 462 | 461 |

(A) Proposed values.

(B) Major insulation requirements up to the 23-kv class are determined to meet surge tests 10 per cent above the flashover of a gap which is 10 per cent higher than the standard gap. In the higher voltage classes the major insulation strength is determined by the requirement that coordination must be obtained at a time lag of 2 microseconds.

(C) Surge strengths divided by $\sqrt{2}$ and by 2.2.

(D) Manufacturers have long recognized the necessity for higher insulation strengths of these transformers, and it has generally been built in.

Any gap used should be protected by lightning arresters, to obtain continuity of service. The discharge voltage of an autovalve arrester for 230-kv service is in the neighborhood of 850 kv. The coordinating gap used might then be set to furnish some desired margin, and in turn a further margin taken for the transformer insulation above the gap. The total of these margins might then be 20 per cent, or 1,020 kv. This impulse strength would correspond to a 60-cycle test voltage of 328 kv. Since the present required test voltage is 461 kv, the possibility of reduction in surge strength requirements by such coordinating means is shown. It should be pointed out that in this case coordination with present designs of bushings would be impossible.

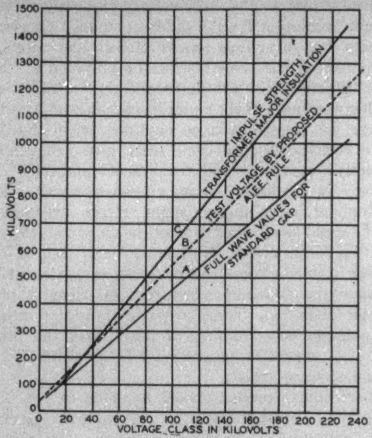

FIG. 12—CURVES SHOWING IMPULSE VOLTAGE REQUIREMENTS OF TRANSFORMERS

*A* gives the full wave values for the standard gaps and for the 1½-40 positive wave and is represented by the equation kv = 30 + 4.22 *L* where kv is the full wave value and *L* is the line voltage in kv. *B* gives the maximum test values according to the proposal of using a gap 10 per cent in excess of the standard gaps, and testing at 10 per cent in excess of the full wave value. The equation for *B* is kv = 36 + 5.1 *L*. *C* represents the voltages to give about 2 microseconds time lag for the standard gaps, and also represents the critical limit for coordination. Where *C* is in excess of *B* it represents the design limit for transformers. The equation for *C* is kv = 6.25 *L*

## SUMMARY

The following conclusions have been reached:

1. The time lag characteristics of major insulation are practically the same for both positive and negative waves.
2. The impulse ratio of major insulation is practically 2.2.
3. The present standard A.I.E.E. tests for the 34.5-kv class and above provide coordination with the proposed coordinating gaps.
4. A.I.E.E. tests below 34.5-kv class are too low and should be increased.
5. Greatest security is obtained if the surge flashover of the bushing is only slightly greater than that of the coordinating gap. A margin of 10 per cent is suggested as the most desirable bushing level.

## ACKNOWLEDGMENT

The author desires to acknowledge the assistance of his associates in the laboratories and engineering departments of the Westinghouse Electric and Manufacturing Company, particularly Messrs. F. D. Fielder, E. J. Grimmer, C. F. Alsing and W. L. Teague, and the helpful criticism of Mr. H. V. Putman in the preparation of this paper.

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## Discussion

For discussion of this paper see page 440.

# Coordination of Insulation

BY V. M. MONTSINGER* Fellow, A.I.E.E.
W. L. LLOYD, JR.* Member, A.I.E.E.
and J. E. CLEM† Member, A.I.E.E.

***Synopsis.**—The general scheme of coordination is discussed. Average circuit insulation used in 1930 is shown. The relation that switching surges and arcing ground overvoltages bear on coordination is discussed giving the number and magnitude of such waves found in service. Levels of insulation in and around the station for outdoor and indoor apparatus are suggested.*

*It is pointed out why a point gap offers the most reliable method of establishing the level for impulse testing of transformers. Also, reasons are given why bushings as made at present should not be used as the sole level for impulse testing.*

*It is shown that on account of the similarity of the volt-time curves for insulations and sphere gaps for short impulse waves, the use of a sphere gap in parallel with a rod gap will give an added protection against direct strokes on or near the apparatus terminals. Also, various proposed schemes are shown to give protection to the transformer and against outages for both fast and slow waves.*

*For potential and current transformers having voltage ratings differing from standard it is suggested that the coordination gaps be selected from the curve of gaps vs. rated circuit voltages.*

*It is shown how an air gap of standardized construction can be used to advantage in expressing the impulse flashover of insulators and bushings. Curves are given showing the gap spacings that are the equivalent in flashover to suspension and pedestal insulators for the ½/5, 1/10 and 1½/40 positive and negative waves. A proposed method to reduce the negative flashover of bushings is given.*

*The effect of the shape of electrodes on the 60-cycle flashover of gaps is discussed and data given. Positive and negative impulse flashover values are given for coordination gaps, standard suspension and pedestal insulators. Also, the effect of humidity on the flashover of gaps and insulators is shown for the ½/5, 1/10 and 1½/40 waves.*

* * * * *

## GENERAL

THE general principle of coordination of system insulation is the selection of insulation in proportion to the anticipated overvoltages. Particularly, the lightning overvoltages are considered as limited by a coordination gap, which thereby establishes the insulation level at which coordination is made. The use of the gap alone does not result in maximum operating reliability. Operating reliability at any system voltage can be increased by liberal use of protective schemes, by increasing the insulation safety factor in relation to the coordination gap, or by increasing the spacing of the coordination gap and establishing coordination at a higher level. On the other hand, proper use of voltage limiting and protective schemes will permit coordination at a lower gap level and reduce costs without sacrificing operating reliability.

In Table I is shown the average circuit insulation for circuits 44-kv and up on lines which were in existence in 1930. It was at first proposed that the adjacent line insulation be used to limit the voltage which might be applied to a station. This was not entirely satisfactory, since the adjustment could be made only in steps of one unit. Also, if the place of flashover can be localized at a point it is more convenient for maintenance of the gap and for the prevention of flashover by lightning arresters. Accordingly, the use of a gap was finally proposed and adopted. This gap is called the "coordination gap" and is used to set a maximum limit to the applied stresses and not as a protective device.

The overvoltages which may appear on a system may be divided into two classes; switching surges and arcing ground voltages in the first class, and lightning impulses in the second class. The overvoltages due to switching and arcing grounds are usually of such a nature that the 60-cycle flashover voltages of the gap and station insulation should be considered in analyzing the possibility of flashover. This conclusion is based on a study[1] of surge voltage recorder records over a period of several years. In this study the wave front of the switching surges was determined. The study of the data indicated that the lower voltage surges had wave fronts relatively slow, while the higher voltage surges had steeper and steeper wave fronts.

TABLE I—AVERAGE CIRCUIT INSULATION

| Nominal circuit voltage | No. units[1] Actual average | No. units[1] Proposed[2] | Coordination gap inches |
|---|---|---|---|
| 13.2 | | | 4 |
| 22 | | | 6¼ |
| 33 | | | 9¼ |
| 44 | 3 | | 12¼ |
| 66 | 5 | 4 | 18¾ |
| 88 | 6 | 6 | 25 |
| 110 | 7 | 7 | 31½ |
| 132 | 10[3] | 8 | 38¾ |
| 154 | 10 | 10 | 44½ |
| 187 | 10 | 12 | 54½ |
| 220 | 13[4] | 14 | 64 |

[1] No. units refers to standard 5¾ in. by 10 in. suspension line insulators.

[2] Originally proposed as reference insulation level.

[3] These are mostly 4¾ in. by 10 in. units—approximately equivalent to 8 standard 5¾ in. by 10 in. units.

[4] Mostly Pacific Coast Region.

In Table II there is shown a tabulation of switching surges covering a period of four years. These data are plotted in Fig. 1. Out of a total of 854 measured switching surges only 4 were above 5 times normal; of these 4, 2 were 5.2 times and 2 were 5.5 times line-to-neutral voltage. It does not seem necessary nor even reasonable to select insulation on the basis of the maximum switching surge overvoltage. There is considerable evidence that if the 60-cycle flashover voltage is more than 4 times normal, there will be very little probability of flashover from switching surges. As a corollary it can

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*General Electric Co., Pittsfield, Mass.

†General Electric Co., Schenectady, N. Y.

1. For references see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

TABLE II—SUMMARY OF RECORDED SWITCHING SURGES 1927-28-29-30[3]

| Power Company | 1 X | 2 X | 3 X | 4 X | 5 X |
|---|---|---|---|---|---|
| | Times Normal Voltage | | | | |
| P. P. & L. | 376 | 243 | 91 | 16 | 4 |
| Ohio Pr. | 329 | 196 | 81 | 21 | |
| N. E. P. | 47 | 27 | 8 | 2 | |
| Ebasco | 57 | 15 | 4 | 2 | |
| N. Y. P. & L. | 45 | 5 | 1 | | |
| Total | 854 | 486 | 185 | 41 | 4[4] |

[1] Includes line to Conowingo.

[2] Miscellaneous properties over the country.

[3] Recorders in 1930 were set so that they did not record any surges less than 1.6 times normal.

[4] Of the 4 above 5 times normal, 2 were 5.5 times.

be stated that there is no need for coordinating the 60-cycle flashover voltage of station apparatus, providing no insulation used has a 60-cycle flashover less than 4 times the normal line-to-neutral voltage of the system.

The overvoltages due to arcing grounds[2] are of the same order of magnitude as the switching surges on an ungrounded system and of lower magnitude on a grounded system. The wave fronts correspond to those of switching surges, so that the insulation requirement should be the same for both switching surges and arcing ground overvoltages. If insulation is satisfactory from consideration of switching surges, it should also be satisfactory in regard to arcing ground overvoltages.

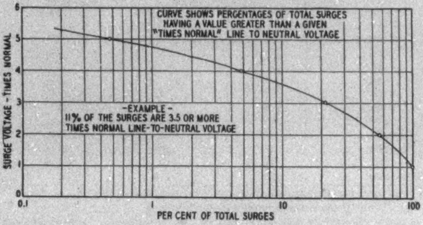

FIG. 1—SWITCHING SURGES—1927-28-29-30

Fundamentally, the lightning overvoltages on the line are independent of and are considerably in excess of any overvoltages set up by the system voltage, and therefore it is only necessary to coordinate with the gap on the basis of lightning overvoltages. The use of a coordination gap at the station to limit the lightning stresses establishes a definite level for design purposes. The line insulation then becomes entirely independent of the station insulation and the line may be designed to suit local conditions. The station insulation can always be referred to the coordination gap for the design level and uniform standards can be set up.

Lightning investigations[3] during the past few years have clearly brought out the fact that lightning impulses occur over a wide range of wave shapes. On this account there is no typical lightning wave. Since the flashover voltage of insulations is affected by the shape of the applied impulse, it is necessary to set up a wave shape, or wave shapes, for coordination purposes. The two most generally used waves have been the ½/5 and 1½/40 microsecond waves. Generally speaking, if coordination is obtained on short waves proper coordination is obtained for longer waves.

Polarity also affects the flashover, the negative wave usually requiring the higher voltage. It is obvious that coordination should be attained in respect to both polarities. It is highly probable that if practical coordination is attained on the positive wave, it will automatically be attained for the negative wave, since the effect of polarity is generally less on gaps than on other apparatus.

It has been proposed from time to time that there be a number of steps or levels of insulation within a station. This is not logical since nothing is gained by increasing the flashover of any part of the station equipment as far as external insulation is concerned. Therefore, the maximum reliability for a given investment is obtained by making the insulation in a station area uniform.

While the obvious place for the coordination gap to limit the lightning overvoltage applied to the station, is at the junction of the line and station, transformers frequently provide a reflection point and accordingly it becomes necessary to locate a coordination gap closely adjacent to the transformer, not more than 100 circuit feet distant for 69 kv and above, and not more than 50 circuit feet distant below 69 kv. This assumes that direct strokes are prevented from reaching the station circuits. Overhead ground wires properly placed provide the best method of accomplishing this.

Thus far the gap has been considered as a device for setting a maximum to the voltage which may be applied to the station apparatus. This gap, however, cannot function unless the applied voltage is greater than the flashover voltage of the gap and, therefore, it offers no relief from repeated application of voltages up to its flashover. When the gap does function an outage results. Accordingly, the gap is not a protective device in the true sense of the word.

The best way to reduce the voltage applied to station apparatus below the limiting value allowed by the coordination gap is through the use of a lightning arrester. The lightning arrester can be designed to reduce all voltages other than direct strokes which are more than a relatively small percentage above the maximum normal frequency voltage and thereby offers protection from overvoltages above this value. Therefore, it increases the operating safety factor between the tested impulse strength of the station apparatus and equipment and the applied impulse voltage. Experience indicates that with modern arresters, gap flashovers are of rare occurrence. The use of the arrester thus prevents interruptions to service by preventing gap flashover, and at the same time absence of gap flashover demonstrates the ability of the arrester to perform its functions satisfactorily.

Since altitude affects the impulse flashover of gaps and other station apparatus similarly the coordination gap should be increased as the air density decreases at the higher altitudes.

### Distribution Voltages

When circuit voltages below 15 kv are considered the problem of coordination becomes very involved. In this region, in addition to transformers, there are generators, motors, and synchronous condensers, as well as switching devices. Here, past practise has not developed insulation strength as great as that in outdoor transformers and station equipment such as bus supports and disconnecting devices. Before the final solution of this problem can be reached, a great deal of further work must be done. Tentatively, equipment in this range may be divided into two classes, "outdoor" and "indoor." The proposed coordination gaps for 13,800, 8,700, and 4,500 volts are 4 in., 3 in. and 2 in. respectively for the "outdoor" classification and might be 3 in., 2¼ in. and 1½ in. respectively for the "indoor" classification.

### Cables

The situation in regard to cables is much more encouraging. While the cable itself is more or less of a protective device and reduces the lightning overvoltages coming in from the line, the insulation strength of the cable and of the pothead should be in line with other station equipment whenever cables are used. When the cable joins two overhead lines the coordination gap should be used to set the maximum voltage and lightning arrester protection[4] should be used if the cable is short enough to need it.

### Transformers

The coordination scheme in respect to transformers is that the transformer bushing be coordinated with the coordination gap and the windings be made stronger than the bushing. The real purpose back of this is a desire to make sure that the transformer bushing can flash over without failure occurring in the windings. Since transformer coordination is to be made on the basis of the bushing, it is obvious that this requires the standardization of the impulse flashover of bushings in reference to the coordination gap for each specific voltage class. Bushings as at present used by the manufacturers have different flashover values and so do not fulfill this requirement. Consequently, the present designs of bushings are not a comparative basis for transformer coordination. It then becomes necessary to set up standards for the impulse strength of bushings. It is proposed that the standard flashover of bushings be 15 per cent higher than the flashover of the coordination gap on impulse.

Since the bushing is to be used as a level for making impulse tests on windings the impulse flashover of all bushings must be standardized. Furthermore, means should be provided for adjusting the arcing distance to get the same kilovolt value under all humidity and air density conditions since the dielectric strength of oil-immersed windings is not affected by changes in the atmosphere. This can be done on General Electric bushings and probably on other types by attaching a short adjustable gap to the base or center clamp which gap will also serve to reduce the negative flashover values.

Again, on account of differences in atmospheric conditions manufacturers are often asked to furnish for the same rated circuit voltage bushings whose creepage distance and arcing lengths are larger than the standard. It is true that oversized bushings can and have been provided in certain cases with gaps to reduce the impulse flashover. Some operators, however, object to gaps on bushings, preferring to depend upon an outside gap to take the flashovers. To require that the winding be stronger than the flashover of these special bushings is unsound economically because to follow this practise would require that the impulse strength of windings be made stronger merely on account of poor atmospheric conditions.

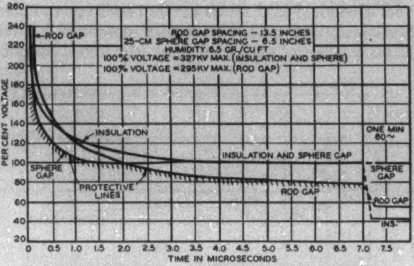

Fig. 2—Relative Impulse Strengths (Volt-Time Curves) of an Insulation Barrier, a Rod Gap and a Sphere Gap—1.5/40 Positive Wave

The sphere gap curve plotted above is not intended to represent the curve of a laboratory sphere gap. It is intended to approximate the curve of a sphere gap as might be affected by dirt and other adverse conditions in practical installation. It is thus a pessimistic curve

The impulse level for which transformers (both windings and bushings) are to be insulated and tested, should therefore be established by something that will give the same results when used by all manufacturers. A standardized air gap is the best device available at the present time.

### Coordination of Transformers with Coordination Gaps

*Waves Other Than Direct Strokes.* The proposed coordination gaps will perform their intended function when subjected to any kind of waves that may come in over the line as the result of induced strokes or of direct strokes on the line out some distance from the station. The rod form of coordination gap has been selected because of its convenience and because it is not readily affected by dirt, corrosion, rain, etc.

*Direct Strokes.* This paper would not be complete, however, if it did not include the results of research and suggestions for protection for very steep front waves that may occur in the rare cases of direct strokes at or very near the terminals of the apparatus. The difference between direct stroke waves and indirect stroke waves is that the former are likely to have very steep fronts whereas the latter have more sloping fronts.

A large number of tests has shown that the margin of safety between a given insulation and a rod gap decreases as the applied wave front decreases or approaches the effect of a direct stroke. Accordingly, if it is desirable to keep a given margin of safety in practise for direct strokes at the apparatus terminals, the rod gap spacings must be less than those applied for the usual conditions.

It is quite important, therefore, to compare the relative dielectric strengths of insulation and coordination gaps for waves with fronts down to a small fraction of a microsecond. Fig. 2 shows curves based upon impulse breakdown tests made on a barrier (described in Table III) composed of solid insulations with intervening oil ducts representing major insulation from high-voltage to low-voltage windings and ground. Solid insulations (pressboard, herkolite, varnished cambric immersed in oil, etc.) have practically the same volt-time characteristics. The rod gap structure used corresponded to that which has been recommended for coordination.

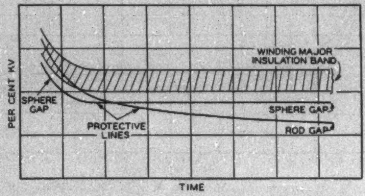

FIG. 3—CHARACTERISTIC VOLT-TIME CURVES FOR TRANSFORMER WINDINGS, A ROD GAP AND A SPHERE GAP

It will be noted that the insulation curve is practically flat down to three microseconds while the gap curve has a sloping characteristic to approximately 0.7 μsec, and for shorter periods rises at a very fast rate. It can be seen, therefore, that with rod gap protection, the factor of safety rapidly diminishes with the steepness of the wave front, particularly for periods at 1 μsec and less. Whether or not these curves cross on a transformer depends upon the insulation margin in the apparatus. However, it was considered of interest to plot these characteristics for a barrier of insulation and gaps. Noting the figure, it is seen that for this particular barrier of insulation the rod gap ceases to give any margin of protection at about 0.8 μsec where the margin is 10 per cent at 2 microseconds. The 10 per cent margin is the same as the proposed difference between the test gap and coordination gap. On this same curve sphere gap characteristics are also shown. In this case the sphere is set to give equal protection as the rod gap at 2 μsec and it will also be noted that the spheres give complete protection down to very short periods of time. Eventually, for the longer periods of time, the insulation curve departs from the sphere gap curve because it must come down to the 60-cycle one minute strength which is in the order of one-half or less than the 1 or 2 μsec gap strength,—the sphere gap curve, of course, remaining flat down to the 60-cycle time. These curves show that for short periods of time, within the direct stroke period, a sphere gap forms the ideal coordination gap.

The one-minute 60-cycle crest breakdown strength of the barrier was 42.5 per cent of the impulse strength, thus giving an impulse ratio of 2.35. This value checks the impulse ratio obtained on sample coil stacks.

In making the impulse tests a 1½/40 positive wave was used. Obviously the breakdown points beyond 1.5 microseconds occurred on the tail of the wave while those for periods of time shorter than 1.5 μsec occurred on the front of the wave (obtained by applying overvoltages of varying magnitudes). In the case where the 0.2 μsec time is shown no series resistance was used in the generator circuit in order to get as steep a wave front as possible.

Fig. 3 shows a sphere gap and a coordination gap applied to transformer insulation. In this particular figure the transformer insulation is represented as a band rather than a line, since it is intended to cover a wide voltage range of different makes and types of transformers.

It is quite evident from the foregoing that if the setting of a rod gap gives reasonable margin for transformer protection for the usual waves coming from the transmission line, it will not give a reasonable margin for direct strokes at or near the terminals.

The most direct way of showing the relative impulse strengths of insulation, a rod and a sphere gap is to show the equivalent gap spacings that represent the breakdown point of the insulation for various overvoltages applied to the insulation. The tests were made by applying a given voltage or overvoltage to the gap and insulation in parallel and increasing the gap setting at 5 minute intervals until the insulation failed. The results are given in Table III.

On the other hand, the rod gap is the ideal coordination gap for the longer waves because of its sloping curve where it follows fairly closely the volt-time characteristics of bushings and other types of station insulators.

A gap having the short time characteristics of spheres and the long time characteristics of rods would be the ideal coordination gap where no other direct stroke protection is provided. Such a gap is available and consists of a sphere gap in parallel with a rod gap. The characteristics of such a gap have been known and it was recommended several years ago.[5]

TABLE III—GAP SPACINGS EQUIVALENT TO THE PUNCTURE OF INSULATION BARRIER*

| ½/5 Positive wave | | | 1½/40 Positive wave | | |
|---|---|---|---|---|---|
| Applied voltage in % of min. full wave to cause breakdown | Gap spacings in inches | | Applied voltage in % of min. full wave to cause breakdown | Gap spacings in inches | |
| | 25 cm spheres | Rod gap | | 25 cm spheres | Rod gap |
| 100 | 5.7 | 14.4 | 100 | 6.5 | 20.5 |
| 125 (approx.) | 5.9 | 12.5 | 135 (approx.) | 7.8 | 17.0 |
| 200 (approx.) | 6.1 | 9.5 | 200 (approx.) | 8.6 | 14.0 |
| 350 (approx.) | | 8.5 | 350 (approx.) | 7.8 | 10.5 |
| 500† (approx.) | 5.7 | 5.5‡ | 500† (approx.) | 5.9 | 6.25‡ |

Note: Humidity of air during rod gap test 1.25 grains per cu ft.

*Composed of 1/8 in. oil, 1/16 in. P. B., 1/8 in. oil, 1/16 in. P. B., 1/8 in. oil between a 4 in. dia. electrode and a large flat plate. In all cases direct puncture of the barrier took place. All values average of at least three tests.

†With zero series resistance in generator circuit.

‡General average of widely varying values.

What are the requirements that such a gap must meet? In the first place, the spheres must be set wide enough so that they will not flash over during switching surges. A safe minimum level for this would seem to be 4 times line-to-neutral voltage as shown elsewhere in this paper. Unfortunately, the 60-cycle wet flashover of spheres horizontally mounted is approximately 50 per cent of the dry flashover. Therefore, an uncovered sphere gap would have to be set for a dry flashover of 8 times line-to-neutral voltage. On this basis the sphere gap impulse flashover would be equal approximately to the ½/5 full wave flashover of the proposed standard coordination gap.

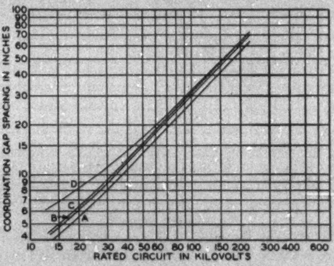

FIG. 4—PROPOSED COORDINATION AND TEST GAP SPACINGS

Also proposed bushing levels expressed in terms of gap spacings that give 50-50 flashover when tested in parallel with bushings with positive impulse waves.

*A*—Proposed coordination gaps
*B*—Proposed test gaps
*C*—Proposed standard bushings
*D*—Proposed special bushings for power transformers

On the other hand, if the spheres are kept dry, by some sort of a covering, so far as switching surges are concerned, a much greater degree of protection to the apparatus could be obtained. That is, the sphere gap could be set for 4 times normal voltage or 50 per cent of that allowable under wet sphere conditions. This low setting, however, would cause an undue number of outages from lightning waves. Somewhere in this wide band is the proper setting to give the maximum benefit compatible with the permissible outages. Just where this point is would no doubt have to be determined by experience in the field, and may vary depending upon local conditions; that is, the frequency of lightning and station design and other protection used. The ideal gap then would be composed of a rod gap in parallel with a covered sphere gap.

There are also possibilities of making a coordination gap composed of two or more gaps in series arranged with shunt capacitance or resistance, etc., so that the time-lag curve is improved as compared with that for a simple rod gap, and which has approximately the same 60-cycle wet and dry flashover values.

Another possible method of obtaining a gap as fast as a single sphere gap (but in less space and possibly at a reduced cost) would be to use a number of smaller spheres in series mounted on or attached to a stack of pedestal insulators with the size and spacing properly adjusted with the voltage gradient along the insulator stack.

The approximate minimum size of spheres for a single gap that would be required for the various circuit voltages is given in Table IV.

TABLE IV

| Rated circuit kv | Diameter of spheres | |
|---|---|---|
| | Cm | Inches |
| 13.8 | 6.25 | 2.47 |
| 23.0 | 12.5 | 4.9 |
| 34.5 | 15.0 | 5.9 |
| 46.0 | 20.0 | 7.85 |
| 69.0 | 30.0 | 11.8 |
| 115.0 | 50.0 | 19.7 |
| 138.0 | 63.5 | 25.0 |
| 161.0 | 75.0 | 29.6 |
| 230.0 | 100.0 | 39.4 |

## APPLICATION OF COMBINATION COORDINATION GAP

The combination gap would be needed only where it is not practical nor economical to provide other adequate forms of direct stroke protection such as overhead ground wires, etc. Very few, if any, modern high voltage stations would really need this gap as the simple rod gap would fulfill the requirements. The combination gap might be used as an added protection to a very important station where other direct stroke protection is provided.

## METHODS TO PROVIDE PROTECTION TO APPARATUS AND AGAINST OUTAGES

In addition to the combination gap another theoretically possible method of protecting the apparatus against strokes would be to provide means for sloping the wave front, thus causing the rod gap to flashover at a lower voltage. It should be kept in mind that slanting the wave front alone (kilovolts remaining the same) does not add any protection to the insulation. In fact, the breakdown voltage of insulation increases for very steep fronts (see Fig. 2). But the advantage of sloping the front comes in due to the fact that the rod gap on account of its volt-time characteristic prevents, by flashing over, the application of excessive voltage to the insulation.

While most schemes suggested for slanting wave fronts are impractical, capacitance seems to be the most promising means. Such a capacitance might be an intervening cable or specially designed capacitor.

The possible combinations for protection to apparatus and against outages for both direct strokes and traveling waves are summarized in Table V.

TABLE V—SHOWING VARIOUS SCHEMES OF PROTECTION AGAINST TRAVELING WAVES AND DIRECT STROKES

| Kind of protection | | | Type of wave for which protection is afforded | |
|---|---|---|---|---|
| Rod gap | Sphere gap | Other protection | (a) To transformer | (b) Against outages |
| Yes | No | None | Traveling wave | None |
| Yes | Yes | None | Traveling wave and direct stroke | None |
| Yes | No | L.A.[1] | Traveling wave | Traveling wave and direct stroke† |
| Yes | Yes | L.A | Traveling wave and direct stroke | Traveling wave and direct stroke† |
| Yes | No | C[2] | Traveling wave and direct stroke | None |
| Yes* | No | L.A. & C | Traveling wave and direct stroke | Traveling wave and direct stroke† |

*Would not be expected to arc when the arrester is operating properly.

†Provided the voltage allowed by the lightning arrester is kept below the flashover of the coordination gap.

[1] Lightning arrester.

[2] Capacitor (to slant the wave front to allow rod gap to take the flashover).

## Coordination of Potential and Current Transformers

The fact that some instrument transformers and other apparatus have voltage ratings (below 13.8 kv) differing from those shown in Table I somewhat complicates the problem of coordination. For example:—2.5 kv, 5.0 kv and 7.5 kv are voltage ratings often used for potential transformers. Rather than attempt to standardize coordination gap spacings for all voltage ratings it is recommended in cases where the voltage rating does not conform to the standard, that the coordination gaps be taken from a curve based on gap spacing *vs.* circuit voltage values given in Table I.

## Transformer Bushing Levels

As pointed out before, the impulse flashover of bushings is subject to some change by slight modification in the design without affecting the 60-cycle flashover values.

Fig. 4 gives the flashover of the proposed standard line of bushings and special bushings for power transformers in terms of equivalent gap spacings. For comparative purposes the coordination and test gap curves are given.

It will be noted that the gap used for making impulse tests (test gap) on transformers is 10 per cent above the coordination gap, and that the proposed standard bushing curve is 15 per cent above the coordination gap throughout. Also, it will be noted that the proposed bushing curve for power transformers is above the curve for standard bushings in the lower voltage range, being as high as 35 per cent above in the 13.8-kv class. The flashover voltage of bushings should be standardized and the bushings should be adjusted to equal the standard.

## Use of Point Gap in Coordination Work

The ideal method of measuring the impulse flashover of gaps, insulators, bushings, etc., would be to use something that has exactly the same flashover characteristics; *i.e.*, has the same humidity and air density, etc., corrections and maintains the same relationship for various waves. If such a device were available and if standard impulse curves were established for this device, when the flashover is desired for a string of special insulators, etc., it would only be necessary to test the insulators in parallel with the device and obtain a balanced condition; that is, obtain 50-50 flashover. This would eliminate the necessity of making corrections for the very troublesome factors such as humidity, air density and would also eliminate any error due to not having the impulse wave exactly of the correct shape. After all, what the operator is interested in most are the "relative flashover values" of the different apparatus. This would give it in the most direct method.

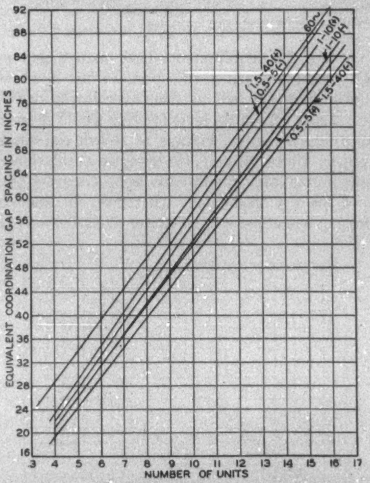

Fig. 5—Curves Showing Gap Spacings that Give 50-50 Flashover when Tested in Parallel with Standard 10-Inch Suspension Insulators, Spaced 5¾ Inches Apart

If the impulse kv values were desired they could be taken from the standard impulse curve for the device.

The coordination gap is not quite the ideal device because its relative or equivalent spacing changes slightly when tested in parallel with suspension and pedestal insulators for various lengths of waves. But considered from the standpoint of humidity and other corrections the gap is nearly ideal because practically the same corrections apply to it as to all other apparatus. The gap method offers a satisfactory means of expressing relative impulse strengths until the kilovolt values can be agreed upon.

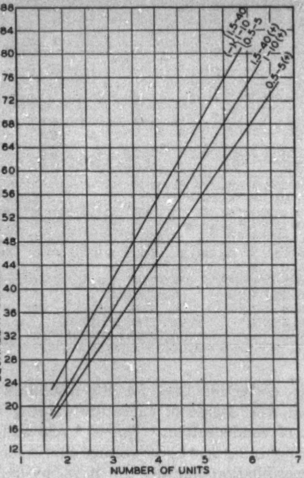

Fig. 6—Curves Showing Gap Spacings that Give 50-50 Flashover when Tested in Parallel with Locke No. 7785 Pedestal Insulators

Figs. 5 and 6 give the equivalent gap spacings (*i.e.*, the spacings that give 50-50 flashover when tested in parallel) for 10 in. suspension insulators and Locke No. 7785 pedestal insulators when tested with the ½/5, 1/10 and 1½/40 positive and negative waves. From these curves we see that the equivalent gaps for 8 suspension insulators are 42 in. and 46 in. for the ½/5 and 1½/40 positive waves respectively. The equivalent gaps for 4 Locke No. 7785 pedestal insulators are 44.5 in. and 49 in. for the ½/5 and 1½/40 positive waves respectively. If for practical purposes the average gap spacings were used, the error would be ± 5 per cent depending upon the wave being considered. This variation, in fact, is no greater and in some cases less than the difference in kilovolt obtained now by the different manufacturers' laboratories. For negative waves for pedestal insulators the equivalent gap values shown on the curve should be used since these are considerably greater than the values for the positive waves. They are the same for all three waves.

It should be pointed out, however, that equivalent gaps for other insulating parts having entirely different time lag characteristics can not be taken directly from standard full wave or minimum flashover curves obtained separately. In such a case it is necessary that the curves for the longer time lag be replaced by curves based upon sufficient overvoltage to make the time lags equal.

The advantages of using a standardized gap for determining and expressing the impulse flashover of other apparatus are as follows:

1. It enables an operator to obtain comparable data from the various manufacturers and thus simplifies the problem of coordination until such a time when the various laboratories can iron out their differences in kilovolt values.

2. It automatically makes correction for humidity and air density; also for slight variations in the wave shape and other factors which affect similarly both the gap and the apparatus under test.

The Pittsfield Laboratory has found that this method of measuring impulse flashover is very convenient and quite practical.

## Sparkover Data

The effect of humidity upon the lightning sparkover voltage of the proposed coordination gap for the 0.5/5, the 1.0/10 and 1.5/40 waves of positive polarity is shown in Fig. 7. This gap consists of square-ended square rods mounted as indicated in Fig. 8.

Similar data for various length strings of standard duty 10 in. by 5¾ in. cemented, cap and pin type, suspension insulators are shown in Fig. 9. From these figures it may be noted that the lightning sparkover voltage of the coordination gap and suspension insulator string increases as the humidity is increased. This is similar to the effect of humidity upon the 60-cycle sparkover voltage of insulators and gaps as previously noted.[6] The effect varies somewhat with the wave-shape. The voltage corrections for the three commonly used light-

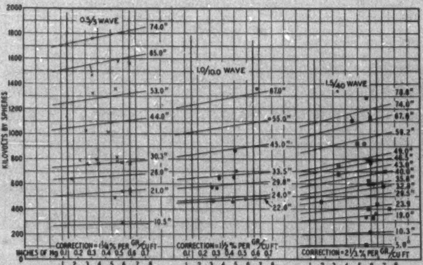

Fig. 7—Effect of Humidity on the Sparkover of Rod Gaps 5/8 In. Square Rods Mounted as Shown in Fig. 8

Positive polarity impulse waves

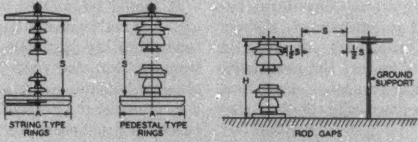

Fig. 8—Recommended Mounting Specifications for Coordination Gaps

| String Type Rings | | | | | Pedestal Type Rings | | | | | | Rod Gaps | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rated Circuit Kv | "S" Ring Separation—Inches | No. Insulators 10″x5¾″ Spacing | % Ring Spacing to Insulator String Length | "A" Dia. of Ring Inches | Rated Circuit Kv | "S" Ring Separation—Inches | Number and Cat. Number | Insulators to Meet Nema Nela Recommendations | % Ring Spacing to Insulator Length | "A" Diameter of Ring—Inches | Rated Circuit Kv | "S" Gap Spacing | Size Square Rod | Locke Ins. | To Meet Nema Recommendations | "H" Inches | Bolts and Bolt Circles | Strength |
| | | | | | | | | Locke O.B. | | | 13.8 | 4.25 | ½″ Sq. cut | 1 | 29150 | 10″ | ½″x 3″ | Standard |
| | | | | | | | | | | | 23 | 6.25 | ½″ Sq. cut | 1 | 29151 | 12″ | ½″x 3″ | Standard |
| | | | | | | | | | | | 34.5 | 9.25 | ½″ Sq cut | 1 | 10455 | 15″ | ½″x 3″ | Standard |
| | | | | | | | | | | | 46 | 12.25 | ½″ Sq. cut | 1 | 9153 | 18″ | ½″x 3″ | Standard |
| | | | | | | | | | | | 69 | 18.75 | ½″ Sq. cut | 2 | 23511 | 25″ | ½″x 3″ | Standard |
| | | | | | | | | | | | | 18.75 | ½″ Sq. cut | 3 | 8888 | 29¼″ | ⅝″x 5″ | Standard |
| 92 | 25.0 | 6 | 72½ | 20 | 92 | 25 | (2) | 7785 26085 | 86 | 30 | *92 | 25.0 | ⅝″ | 2 | 7785 | 29″ | | |
| 115 | 31.50 | 8 | 68½ | 30 | 115 | 31.5 | (3) | 7785 26085 | 72 | 36 | 115 | 31.5 | ⅝″ | 3 | 7785 | 43½″ | ⅝″x 5″ | Light |
| 138 | 38.25 | 9 | 74 | 30 | 138 | 38.25 | (4) | 7785 26085 | 66 | 36 | 138 | 38.25 | ⅝″ | 4 | 7785 | 58″ | ⅝″x 5″ | Medium |
| 161 | 44.50 | 11 | 70½ | 36 | 161 | 44.5 | (4) | 7785 26085 | 77 | 36 | 161 | 44.5 | ⅝″ | 4 | 7785 | 58″ | ⅝″x 5″ | High |
| 196 | 54.50 | 13 | 73 | 40 | 196 | 54.5 | (5) | 7785 26085 | 75 | 40 | 196 | 54.5 | ⅝″ | 5 | 7785 | 72½″ | | |
| 230 | 64.0 | 16 | 69½ | 40 | 230 | 64 | (6) | 7785 26085 | 74 | 40 | 230 | 64 | ⅝″ | 6 | 7785 | 87″ | ⅝″x 5″ | High |

*Not listed in Nema Recommendations.

ning waves and for 60 cycles are approximately as follows:

| | |
|---|---|
| 0.5/5 wave | 1¼% per grain per cu ft |
| 1.0/10 wave | 1½% per grain per cu ft |
| 1.5/40 wave | 2⅓% per grain per cu ft |
| 60 cycles | 3.0 % per grain per cu ft |

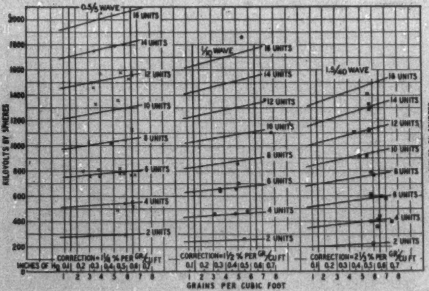

Fig. 9—Effect of Humidity on the Sparkover of Standard 10-Inch Suspension Insulators Spaced 5¾ Inches Apart

Positive polarity impulse waves

The corrections appear to continue as nearly straight lines up to at least 16 grains per cubic foot and to be very nearly the same for both insulators and coordination gaps, if precautions are taken to prevent condensation on the porcelain surfaces of the insulators at the higher humidities. Unless these precautions are taken curved humidity correction lines for the insulators may be measured, the degree of curvature varying with the amount of condensation. The 60 cycle and positive polarity lightning sparkover voltage curves for the proposed coordination gap and the 10 in. by 5¾ in. suspension insulator at an absolute humidity of 6.5 grains per cubic foot (14.87 grams per cubic meter) are shown, respectively, in Figs. 10 and 11.* This absolute humidity corresponds to a vapor pressure of 0.6085 inches (15.45 mm) of mercury and a relative humidity of 65

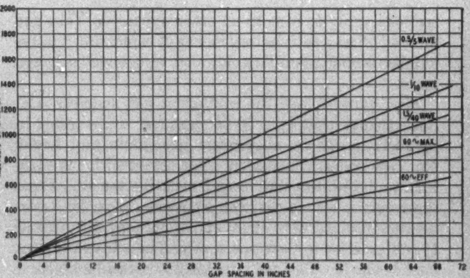

Fig. 10—Sparkover of Rod Gaps

5/8-inch square rods mounted as shown in Fig. 8. Humidity 6.5 grains/cu ft. Positive polarity impulse waves per cent at 77 deg F (25 deg C) and a barometric pressure of 30.0 inches (76.2 cm) of mercury.

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*Measured points can not be given on these two figures since these curves are derived curves plotted from the data given in the two preceding figures for which the measured points are plotted.

In the A.I.E.E. Standards 41, dated March, 1930, on "Insulator Tests" it is stated that "flashover voltage shall be determined at or corrected to a standard humidity corresponding to a vapor pressure of 0.6085 in. (15.45 mm) of mercury. This is equivalent to a relative humidity of 65 per cent at 77 deg F (25 deg C) and a barometric pressure of 30.0 in. (76.2 cm) of mercury." Since it has been shown[6] that the flashover voltage varies with the absolute humidity rather than with the relative humidity, it is felt that reference to the relative humidity should be omitted. Also, since grains per cubic foot or grams per cubic meter is believed to be a term which is in more general use and one which conveys a somewhat greater meaning to the average engineer than does the term vapor pressure in inches or millimeters of mercury, it is suggested that the Institute Standards be changed to express absolute humidity in terms of grains per cubic foot (grams per cubic meter).

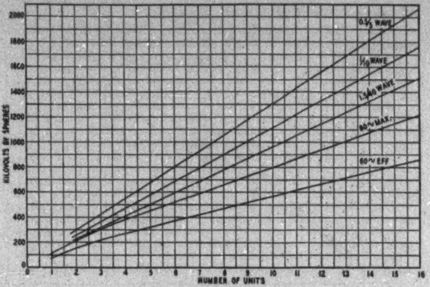

FIG. 11—SPARKOVER OF STANDARD 10-INCH SUSPENSION INSULATORS

Spaced 5¾ inches apart
Humidity 6.5 grains cu ft
Positive polarity impulse waves

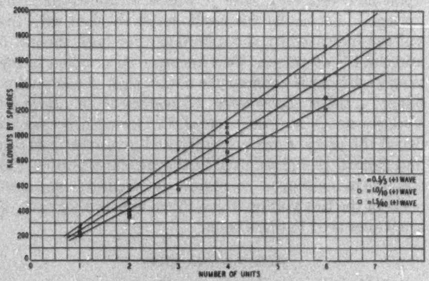

FIG. 12—SPARKOVER OF LOCKE NO. 7785 PEDESTAL INSULATORS

Humidity 6.5 grains/cu ft
Positive polarity impulse waves

Fig. 12 presents the positive polarity lightning sparkover voltage curves for a heavy duty pedestal insulator commonly used for high voltage bus insulation in outdoor stations. The curves are plotted for an absolute humidity of 6.5 grains per cubic foot.

The negative polarity sparkover voltage curves of the coordination gap at a humidity of 6.5 grains per cubic foot are given in Fig. 13. While the negative data are not as extensive as the positive data, the negative short wave sparkover voltage of the coordination gap appears to be approximately the same as the positive short wave sparkover voltage, whereas the negative long wave sparkover voltage is appreciably higher than the positive long wave sparkover voltage.

The negative polarity sparkover voltage curves for various length strings of 10 in. by 5¾ in. suspension insulators at a humidity of 6.5 grains per cubic foot are given in Fig. 14. In contrast with the results obtained on the coordination gap, the negative short wave sparkover voltage of the insulator string is higher than the positive short wave sparkover voltage, whereas the negative long

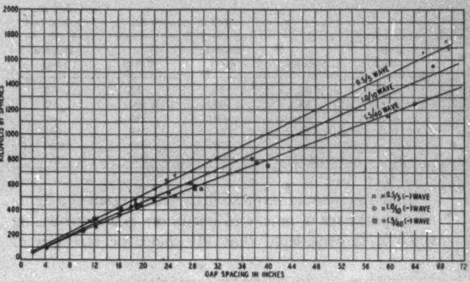

FIG. 13—SPARKOVER OF ROD GAPS. 5/8-INCH SQUARE RODS

Mounted as shown in Fig. 8
Humidity 6.5 grains/cu ft
Negative polarity impulse waves

TABLE VI—COORDINATION GAP—1.5/40 WAVE

| | Negative polarity | | Positive polarity | |
|---|---|---|---|---|
| Setting | Dry | Wet | Dry | Wet |
| 12 in. | 265 | 285 | 241 | 245 |
| 18 in. | 425 | 415 | 332 | 335 |
| 24 in. | 535 | 515 | 425 | 400 |

Suspension Insulators—1.5/40 Wave

| | Negative polarity | | Positive polarity | |
|---|---|---|---|---|
| No. of disks | Dry | Wet | Dry | Wet |
| 2 | 225 | 200 | 225 | 205 |
| 4 | 410 | 390 | 410 | 415 |
| 6 | 595 | 550 | 595 | 565 |

Disks are standard duty 10 in. by 5¾ in. cap and pin type units.

Artificial rain 0.2 in. per min. at 45 deg. Resistance = 15,000 ohms per cubic centimeter.

Temperature of water approximately 60 deg F (15 deg C).

Dry sparkover values corrected to unity air density and 6.5 grains per cubic foot (14.87 grams per cubic meter) absolute humidity.

wave sparkover voltage appears to be approximately the same as the positive long wave sparkover voltage.

The negative polarity lightning sparkover curves for station-bus pedestal insulators at 6.5 grains per cubic foot are given in Fig. 15. The negative short wave sparkover voltage appears to be approximately 20 per cent higher than the positive short wave sparkover voltage. The negative long wave sparkover voltage appears to be approximately 30 per cent higher than the positive long wave sparkover voltage.

Table VI gives some recent data on the effect of rain upon the lightning sparkover voltage of the coordination gap and the suspension insulator. The results are in agreement with the earlier tests.[6] The effect of rain varies from zero to 10 per cent with the long wave while with the short wave the effect is practically negligible.

TABLE VII—60-CYCLE DRY FLASHOVER KV EFFECTIVE (APPROXIMATE)

| | | 5/8 in. square rod | | 5/8 in. round rod |
|---|---|---|---|---|
| Gap inches | Needles | Square ends | Horns | Square ends |
| 2 | 35 | 40 | 55 | 55 |
| 4 | 55 | 60 | 100 | 90 |
| 8 | 90 | 100 | 180 | 150 |
| 12 | 120 | 125 | 215 | 195 |
| 16 | 155 | 160 | 240 | 220 |
| 24 | 220 | 230 | 280 | 255 |

That rain should have so little effect upon the lightning sparkover of gaps and insulators is not surprising when it is considered that the dielectric strength of water for impulse voltages is from 2 to 14 times the dielectric strength of air.[7]

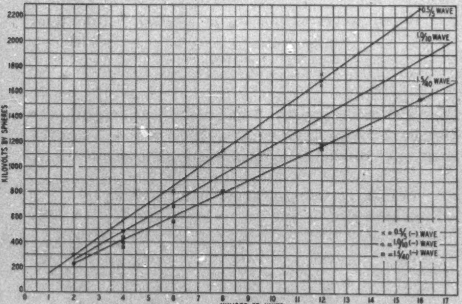

Fig. 14—Sparkover of Standard 10-Inch Suspension Insulators, Spaced 5¾ Inches Apart

Humidity 6.5 grains/cu ft
Negative polarity impulse waves

Table VII gives the 60-cycle dry flashover values of gaps having electrodes of different shapes.

The majority of the sparkover data presented in this paper was obtained in the High Voltage Engineering Laboratory in Pittsfield, Mass. Certain check tests, however, were conducted in the General Engineering Laboratory in Schenectady. Although the equipment, method of procedure and general technique followed in the two laboratories are quite different, the results checked within a few per cent. In both laboratories, the voltage is determined directly by means of the sphere-gap, as recommended by the A.I.E.E. Standards 41.

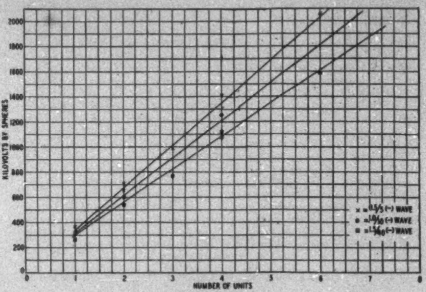

Fig. 15—Sparkover of Locke No. 7785 Pedestal Insulators

Humidity 6.5 grains/cu ft
Negative polarity impulse waves

It is also possible to measure the test voltage by means of oscillograph deflection if a voltage divider is used which reduces the test voltage to that applied to the oscillograph without introducing or eliminating superimposed oscillations on the indicated wave. By developing an accurate divider, this method of voltage measurement has also been employed in the Schenectady laboratory and in Pittsfield. Such measurements were depended upon however, only after it was determined that the voltage indicated by the oscillograph checked with the voltage indicated by the sphere gap for both the 0.5/5 and the 1.5/40 waves. Very accurate adjustment of the voltage divider is necessary to obtain this. A companion paper entitled *Laboratory Measurement of Impulse Voltages* by C. M. Foust and J. C. Dowell describes in detail the precautions necessary and gives the methods and general technique used in the two laboratories, the equipment employed to obtain an accurate measurement of the test voltage wave-shape and oscillograms of the waves used in these tests.

### ACKNOWLEDGMENT

The authors desire to express their appreciation for the helpful suggestions made by Messrs. F. W. Peek, Jr., K. B. McEachron and L. Wetherill.

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## Discussion

For discussion of this paper see page 440.

# Impulse Voltage Testing

BY C. F. HARDING[1] and C. S. SPRAGUE[2]
Fellow, A.I.E.E. Associate, A.I.E.E.

IN a recent paper before the Institute,[3] the authors presented the results of tests of a standard 2,300-4,000 to 115/230-volt distribution system upon which both induced and direct-stroke surge potentials were impressed as the result of the sudden charging of a thoroughly insulated cloud supported over the line. These tests were carried out as the result of the cooperation of the Utilities Research Commission of Chicago.

The four conclusions reported in the previous paper which are of particular interest and therefore worthy of the further study described in this paper are as follows:

In existing transformer design the insulation of the secondary winding may be overstressed by steep wave front surges without excessive stress on the primary insulation; such stresses may be relieved by improvements in secondary insulation.

Interconnecting the primary lightning arrester ground to the grounded neutral of the secondary main greatly reduces the voltages at the transformer and imposes no extra hazard upon the consumer's wiring.

Using "direct strokes" from the surge generator, the interconnection is of great benefit with high arrester ground resistances. With any combination of secondary neutral and arrester ground resistances, the interconnection limits the transformer stress to the value determined by the arrester voltage, and should reduce materially the lightning failures on non-surge-proof types of transformers.

With usual city conditions, consisting of a multiplicity of low resistance grounds on the secondary neutral, and the further possibility in some instances of a lightning arrester ground of high resistance, it has been demonstrated herein that potentials at the transformer may be reduced greatly by the interconnection of the primary lightning arrester ground and the grounded neutral of the secondary main.

During the course of these tests, the insulation of several of the non-surge-proof transformers was punctured while operating temporarily without the interconnection but with lightning protection having a high resistance ground. There is no doubt but that these break-downs of insulation would have been avoided had the conditions of this experimental investigation permitted operation with the interconnection at all times. Thus it is believed that a further protective method has been demonstrated for the thousands of the older types of distribution transformers now in service which, of course, must be retained in use for many years.

It was soon evident, however, that certain changes in the design and construction of these transformers would cause them to be practically surge proof. Transformers of various manufacturers' designs were tested subsequently, in the high potential surge laboratory. They withstood all of the exposures when provided with lightning arresters or equivalent internal protection. However, in the event of transformer installation without such lightning arrester protection or, in case of the failure of such protective devices to operate, the surge flashover of bushings and the insulation puncture values of the different types of transformers differ widely and provide undetermined factors of safety. Herein lies the line of demarcation, at the present time, between the various types of distribution transformers of the so-called surge-proof design and construction. Shall the prospective purchaser be content to depend upon either external or internal protective devices or shall he insist upon certain specified factors of safety for the bushing flashover and the insulation puncture values above the protective gap flashover value?

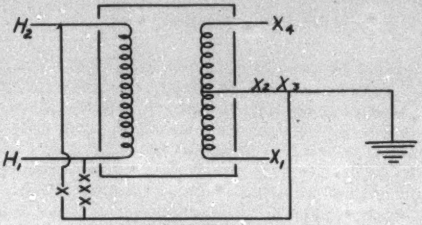

FIG. 1—CIRCUIT DIAGRAM FOR SURGE TESTS WITH EXTERNAL ARRESTERS

XXX = phase arrester
X = neutral arrester
Surge applied at $H_1$

## SURGE TESTS ON DISTRIBUTION TRANSFORMERS

The first tests consisted of impressing surges upon each transformer between primary phase lead $H_1$ and secondary neutral $X_2$, $X_3$, as indicated in Figs. 1 and 2. In these tests the case was ungrounded and the primary phase and neutral arresters were connected between the respective primary terminals and the grounded secondary neutral. It will be seen that this connection is equivalent to employing, in service, the interconnection of the secondary neutral and the primary lightning arrester ground.

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[1] Head, School of Electrical Engineering, Purdue University.

[2] Research Assistant, Engg. Exp. Station, Purdue University.

[3] *Tests on a Typical Urban Circuit* by C. Francis Harding and C. S. Sprague, ELECTRICAL ENGINEERING, September 1932 based upon *Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main* (No. **32-16**) A.I.E.E., TRANS., March 1932, p. 234. Revised especially for ELECTRICAL ENGINEERING and brought up to date.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

As shown in the oscillogram of Fig. 3 the applied test wave had a peak value of 182 kv with the voltage increasing at an average rate of 50 kv per microsecond on the major part of the wave front. This wave was adopted by the committee of the Utilities Research Commission in charge of the project as being more representative of the wave which was more liable to reach the average distribution transformer than the steeper waves. Also, since the transformers were to be tested with arrester protection, this wave more nearly approximates the specifications for lightning arrester testing.

With arrester protection as described above the following readings of Table I and oscillograms Figs. 4 to 6 were taken of the voltages on the transformer.

Primary Phase to Secondary Neutral, Fig. 4
Primary Phase to Case
Primary Neutral to Secondary Neutral, Fig. 5
Primary Neutral to Case
Secondary Neutral to Case, Fig. 6
Case to Secondary $X_1$
Case to Secondary $X_2$

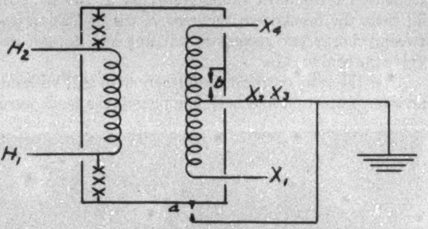


Fig. 2—Circuit Diagram for Surge Tests With Internal Protection

$a$ Case to ground-lead gap
$b$ Case to secondary neutral gap
Surge applied at $H_1$

Note: Arresters connected to secondary neutral when gaps $a$ and $b$ are not supplied

The oscillogram of Fig. 5 indicates the potential between the primary neutral and the secondary neutral of transformers Nos. 1 and 4 with the primary neutral arrester connected but evidently not operating. Another exactly similar oscillogram, but without the neutral arrester connection, indicated by its similarity to Fig. 5 that the neutral arrester had not operated in the former test. Fig. 6 illustrates how the potential of the ungrounded transformer case floats close to the potential of the secondary neutral. For one of the transformers with internal protection, with the primary arrester discharging into the case, Fig. 7 shows that the potential of the case floats close to the secondary neutral until the primary arrester breaks down, at which time the potential between the case and the secondary neutral rises to the break-down value of the coordinating gap between case and ground. Fig. 8 shows the arrester current for the external arrester used in these tests. A maximum of 1,670 amperes was obtained in approximately 8 microseconds. Essentially the same current was obtained with the internal gaps.

From the data of Table I, it will be noted that the external lightning arrester connected between the primary phase and the secondary neutral limits the voltage across the transformer to about 19 kv. In the case of the transformer No. 6 with inclosed arresters the maximum voltage was 53.8 kv. While this illustrates the beneficial effect of the interconnection, it is obvious that the transformer insulation was not subjected to a very severe test.

The voltages measured between the primary phase lead and the case, and between the case and the secondary neutral indicate that the ungrounded case assumes a potential close to that of the secondary winding. With transformer No. 6, however, the inclosed arresters discharge into the case and raise the potential between the case and the secondary to that determined by the breakdown of the case-to-ground, or the case-to-secondary-neutral gap, depending upon which gap was allowed to spark over in the tests. The surge breakdown of the case-to-ground gap was found to be 22.8 kv, that of the case-to-neutral gap was found to be 31.4 kv. For the transformer No. 6 the reading from the primary phase to the case gives the maximum arrester potential, in this instance 35.6 kv.

TABLE I—SURGE TESTS ON DISTRIBUTION TRANSFORMERS WITH ARRESTER PROTECTION

| | |
|---|---|
| Peak Voltage of Applied Wave | 182 Kv |
| Wave Front Steepness | 50 Kv/μs |
| External Arresters Used: | 3-5 Kv on Primary Phase Leads and 300-Volts Neutral Arrester in Primary Neutral |

| | | Transformer voltage kv | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Transformer No. | Arresters | Prim. $H_1$ to sec. neut. | Prim. $H_1$ to case | Prim. $H_2$ to sec. neut. | Prim. $H_2$ to case | Case to sec. neut. | Case to sec. $X_1$ | Case to sec. $X_2$ |
| 1 | External | 16.9 | 15.4 | 4.1<br>4.7[1] | 2.9 | 4.0 | 2.8 | 2.2 |
| 2 | External | 18.3 | 16.9[2] | 7.9<br>22.2[1] | 6.9 | 3.4 | 1.9 | 1.7 |
| 3 | External | 20.0 | 19.5[2] | 8.1<br>23.2[1] | 6.5 | 2.1 | 2.0 | 2.0 |
| 4 | External | 18.0 | 16.0 | 4.6<br>5.2[1] | 3.1 | 3.3 | 3.7 | 3.5 |
| 5 | External | 19.0 | 16.4 | 8.9<br>9.1[1] | 7.1 | 2.4 | 3.6 | 2.6 |
| 6 | Internal | *53.8<br>†53.2 | 35.6 | 15.3 | 9.5 | 22.8<br>31.4 | 22.1 | 16.4 |
| 7 | Internal | 15.9 | 13.0 | 6.7 | 5.25 | 2.7 | 2.6 | 2.1 |
| 8 | None | 20.0<br>‡87.6 | | | | | | |
| 9 | None | 19.4<br>§84.0 | | | | | | |

[1] These readings taken with primary neutral arrester disconnected.

[2] Heavy discharge on measuring gap indicating breakdown from case to secondary after measuring gap sparked over.

*Using both case to ground and case to neutral gaps.

†Using case to neutral gap only.

‡Path of flashover, inside case, phase lead to case 1-3/16 in., case to sec. lead 1-1/8 in.

§Path of flashover, primary phase lead to case, outside over bushing, 1 in., core bolt to secondary jumper, inside ⅛ in.

Voltages between the primary neutral and the secondary neutral were in some cases not sufficient to operate the 300-volt primary neutral arrester. Transformers Nos. 2 and 3 showed, with the primary neutral arrester removed, a voltage between the primary neutral and the secondary neutral somewhat higher than that between the primary phase and the secondary neutral. This seems to indicate that the primary windings of these transformers had broken down between turns or layers. The reconnection of the neutral arrester reduced the voltage on the primary neutral to about 8 kv indicating that this value was the surge breakdown of these arresters. The oscillograms of Fig. 9A and B illustrate the potentials between the primary neutral and the secondary neutral with and without the use of a primary neutral arrester connected as in Fig. 1. It may be noted here that transformers Nos. 2 and 3 were the same ones which indicated breakdown under direct stroke tests on the experimental distribution line. It was also noted in the laboratory surge tests on these two transformers, that when measuring the voltage between the primary phase and the case, a heavy discharge was obtained across the measuring gap, indicating the probable breakdown between the case and the grounded secondary.

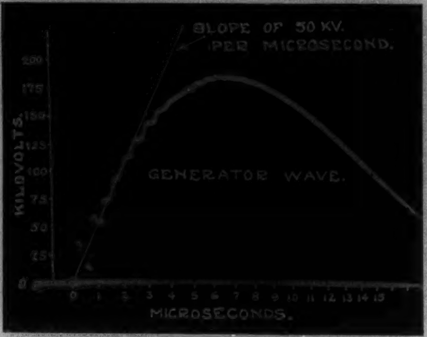


Fig. 3—Generator Wave

It was not considered feasible to energize the transformers when tested on the line. However, in tests where the insulation between turns or layers may be punctured, the transformer may be energized as a means of detecting this type of breakdown which might not be apparent otherwise.

Two of the older transformers, Nos. 8 and 9, not of the surge proof type, were tested, and showed no evidence of damage with arrester protection. The arresters were removed and the voltage increased until bushing flashover occurred at approximately 85 kv as noted in the table.

In addition to the surge tests of the transformers with protection, four transformers were tested without protection up to the point of insulation failure. As before the surge was applied between the primary phase lead and the secondary neutral lead. For these tests without protection a ½-10 wave was used. The peak voltage of the wave was increased gradually until failure of the transformer insulation occurred. With this type of test the breakdown would naturally occur on the tail of the wave. Table II presents the data obtained on these transformers.

TABLE II

| Transformer | Surge kv* | Remarks |
|---|---|---|
| *A* | 125 | Flashed over from the primary lead to the case and to the secondary lead over the surface of the oil |
| *A* | 162 | Insulation punctured |
| *B* | 146 | Flashed over from the primary lead to the case and to the secondary lead over the surface of the oil |
| *B* | 162 | Insulation punctured |
| *C* | 146 | Insulation punctured |
| *D* | 103 | Insulation punctured |

*Peak value of ½-10 wave.

Table II indicates for these transformers a range of insulation breakdown values from 100 to 160 kv. In all cases the breakdown occurred in the insulation between primary and secondary winding and did not involve the core or case.

After the tests on the transformers with and without arrester protection had been completed, the leads were disconnected from the windings and the following bushing flashover tests were performed:

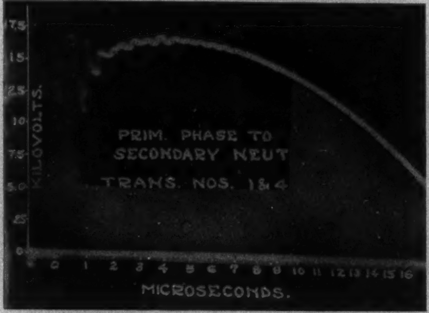


Fig. 4—Surge Potentials on Transformers With External Arrester Protection

Wet and dry flashover outside
Dry flashover inside

Each of the above flashover tests was made with 60-cycle voltage, with a 50 kv per $\mu$sec front surge, and with a 150 kv per $\mu$sec front surge.

Some of the transformers had their primary leads taped with several layers of varnished cambric. With this lead insulation the primary bushings withstood surges of 100-kv peak value. Since this value seemed to be of the order that might be expected of the winding insulation, the tests were not carried to the point of puncturing the lead insulation or flashing the primary bushings. Instead, a piece of No. 22 copper wire was coiled around the lead insulation as close as possible to the bushing and connected to the lead. This approximated the condition of completely deteriorated insulation on the leads of the transformers of this type. The values given in the following table apply to this condition.

With the transformers Nos. 1 and 4 the outside of the bushings was taped and painted in accordance with the standard specification of the Commonwealth Edison Company. For transformer No. 1 the bare metal was exposed inside the tank and there was no problem of lead insulation, while for transformer No. 4, extra leads were used in place of those furnished with the transformer, in order to avoid cutting the existing leads.

All flashover tests were conducted in accordance with the A.I.E.E. standard specifications for this type of testing.

The following Table III presents the flashover values of the transformer bushings.

TABLE III—60-CYCLE AND SURGE FLASHOVER OF TRANSFORMER BUSHINGS

60-Cycle and Surge Flashover of Transformer Bushings

| | |
|---|---|
| Barometer | 747-756 Mm |
| Temperature | 24-26° C |
| Humidity | 40-70% |
| Precipitation (For Wet Flashover Tests) | 0.192-0.205 In./Min |
| Water Resistivity (For Wet Flashover Tests) | 6,550 Ohms/Cu In. |

| | | Prim. phase or neutral bushing | | | Secondary bushing | | |
|---|---|---|---|---|---|---|---|
| | | Outside | | Inside | Outside | | Inside |
| Transformer No. | Type of voltage | Dry | Wet | Dry | Dry | Wet | Dry |
| 1 | 60 cycle (eff.) | 49.0 | 33.0 | 32.6 | 48.3 | 31.3 | 32.6 |
| | 50 kv/μs | 106.0 | 133.0 | 61.0 | 101.0 | 101.0 | 66.5 |
| | 150 kv/μs | 109.0 | 107.0 | 82.0 | 109.0 | 102.0 | 84.5 |
| 4 | 60 cycle (eff.) | 53.6 | 27.0 | 40.6 | 53.3 | 29.8 | 41.3 |
| | 50 kv/μs | 96.0 | 109.0 | 109.0 | 99.0 | 100.0 | 100.0 |
| | 150 kv/μs | 107.0 | 100.0 | 109.0 | 111.0 | 101.0 | 109.0 |
| 5 | 60 cycle (eff.) | 33.3 | 17.7 | 26.9 | 24.2 | 14.6 | 16.9 |
| | 50 kv/μs | 96.0 | 78.0 | 54.5 | 50.0 | 50.0 | 31.5 |
| | 150 kv/μs | 100.0 | 85.3 | 67.3 | 52.0 | 52.0 | 38.2 |
| 6 | 60 cycle (eff.) | 36.9 | 26.8 | 22.3 | 35.0 | 20.2 | 14.2 |
| | 50 kv/μs | 96.0 | 91.2 | 52.5 | 76.5 | 74.0 | 33.0 |
| | 150 kv/μs | 102.0 | 102.0 | 57.5 | 83.5 | 80.5 | 37.0 |

The data of Table III reveal, in general, that transformers Nos. 1 and 4 have somewhat higher bushing flashover values, especially inside the tank, than do Nos. 5 and 6. Transformer No. 4 shows higher flashover values inside the tank than does transformer No. 1. Of course, in making comparisons from the figures of the table it must be remembered that the flashover values of transformers Nos. 5 and 6 apply to the condition of completely deteriorated lead insulation.

A considerable variation is noted in the flashover values, outside the tank, of transformers Nos. 1 and 4. It seems evident that these are due to variations in the taping and painting of the bushings. Reasonable care was used in this operation but evidently uniform results were not obtained. It was interesting to note, during the tests, that in practically all cases the 60-cycle flashover punctured the tape, while the surge flashover went underneath the tape.

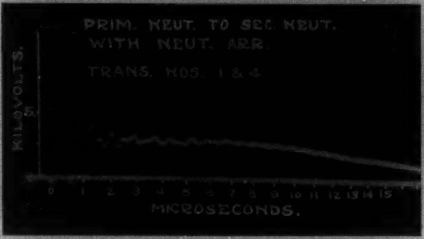


Fig. 5—Surge Potentials on Transformers With External Arrester Protection

With the 60-cycle bushing flashover inside the tank of transformer No. 4, the values in the table are the values of the first flashover. A large amount of carbonization occurred and unless the leads were removed and the bushings cleaned, the 60-cycle flashover value was observed to drop to 65 or 75 per cent of its initial value. This trouble was not noticeable to any extent on the surge flashover tests. It was observed that the inside bushing flashover of the transformer No. 4 did not puncture the lead insulation but followed the surface of the porcelain into the metal of the lead.

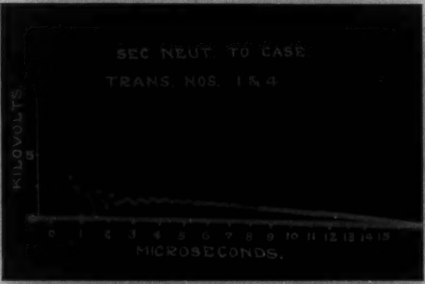


Fig. 6—Surge Potentials on Transformers With External Arrester Protection

The data of the table also indicate that the surge flashover under rain conditions is not materially different from that under dry conditions. In this respect it may be noted here that one of the transformers, in contrast to the others, was designed so that very little of the drip from the tank fell upon the bushings.

As mentioned previously, the coil insulation of some of the transformers did not receive a severe test. It seemed desirable to determine the effects of a more severe surge upon the windings of the transformers. Accordingly the insulation between the primary and the case on some of the transformers was tested up to the point of primary bushing flashover inside the case as listed in the table. No evidence of insulation damage was noted in these tests.

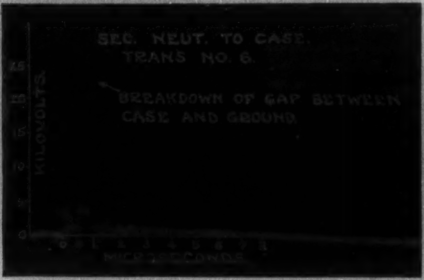


FIG. 7—OSCILLOGRAM SHOWING THE POTENTIAL BETWEEN THE CASE AND THE SECONDARY FOR THE TRANSFORMER WITH INTERNAL ARRESTERS DISCHARGING INTO THE CASE

Some tests were also made to determine the recovery value, if any, of punctured insulation as the result of the oil filling up the puncture. The two transformers, which in the previous tests had indicated breakdown between the secondary winding and the case, were subjected to surges up to the point of breakdown between the secondary and the case. The following values were obtained in this test.

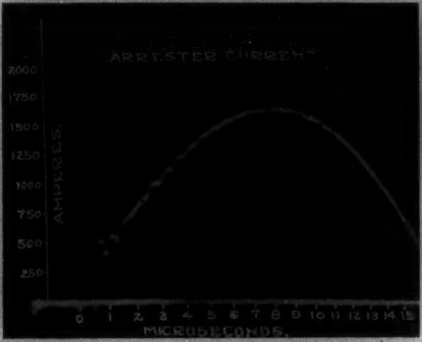
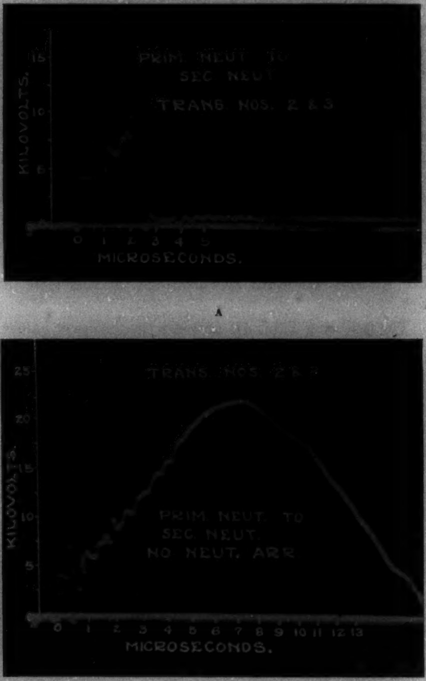


FIG. 8—ARRESTER SURGE CURRENT

| Transformer | Breakdown test secondary to case | Oil test |
|---|---|---|
| No. 2 | 56 kv | 24.8 kv |
| No. 3 | 17 kv | 25.5 kv |

These values would seem to indicate that a transformer in service might have its insulation punctured by a surge and still have sufficient insulation for normal line potential. If the transformer fuse is blown, there is necessarily some interval before it is replaced. This allows time for the oil to fill the puncture so that when the fuse is replaced the transformer continues to operate as before. Such has been the experience of many companies.



A

B

FIGS. 9A AND 9B—OSCILLOGRAMS OF POTENTIALS BETWEEN PRIMARY NEUTRAL $H_2$ AND SECONDARY NEUTRAL $X_1X_4$ ON TRANSFORMER WITH PREVIOUSLY BROKEN DOWN INSULATION

Oscillogram A with 300-volt neutral arrester
Oscillogram B with no neutral arrester

## CONCLUSIONS

1. With usual city conditions, consisting of a multi-

plicity of low resistance grounds on the secondary neutral, and the further possibility in some instances of a lightning arrester ground of high resistance, it has been demonstrated that the interconnection definitely limits transformer stresses to values which should reduce lightning failures to a practically negligible quantity, even with the older non-surge-proof types of transformers.

2. There should be a reasonable ratio between coil insulation puncture value, bushing flashover value on the inside of the tank and bushing flashover value outside of the tank.

3. Surge-proof transformers should have a reasonable factor of safety between insulation puncture strength and minimum bushing flashover values which should occur outside the tank to assure, in case of failure of protective equipment, that the transformer insulation will not be damaged.

4. Conclusion 3 represents the more or less ideal case. If extensive use of the interconnection results in reducing flashovers and punctures to a negligible number with non-surge-proof transformers, the added cost of the surge-proof type may be warranted only for special installations.

5. In general, reflections are produced across the series resistance of the surge generator discharge circuit depending upon the magnitude of the series resistance and the constants of and lengths of wire in the circuit. The magnitude of these reflections may be reduced by the capacitance of potentiometers, sphere gaps or the load itself.

6. The use of ultra-violet illumination of sphere gaps is conducive to greater accuracy and consistency of potential measurement, especially with potentials having steep-wave fronts and with the use of smaller spheres and gap spacings.

7. In making surge tests on transformers, the natural exposures will be most closely duplicated if surges are impressed between primary phase lead and grounded secondary neutral.

8. It seems likely that the insulation of transformer coils may be punctured by an impulse voltage and at a later time withstand line voltage.

### ACKNOWLEDGMENT

The authors appreciate very greatly the cooperation of the Utilities Research Commission and particularly the assistance of its committee of engineers of affiliated operating companies for whom Mr. D. W. Roper acted as chairman. Messrs. J. S. Malsbary and H. Creviston, graduate students, and several others who assisted in the routine testing and the analysis of data are complimented by the authors for their enthusiastic interest and cooperation.

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## Discussion

For discussion of this paper see page 440.

# Protection of Rotating A-C Machines Against Traveling Wave Voltages Due to Lightning

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***Synopsis****—The problem of providing protection for rotating a-c machines against lightning overvoltages has two parts:*

*1. The protection of insulation to ground, which is mainly a question of the magnitude of the overvoltage, and*

*2. The protection of turn insulation, which is primarily a matter of wave front.*

*To meet the first requirement, the overvoltage to ground must be limited to a safe value. This is assumed to be approximately equal to the crest value of the 60-cycle high potential test. To fulfill the second requirement, the turn voltage gradient must be limited to conform to the turn insulation.*

*To secure these results, a protective scheme is proposed, which includes arresters 2,000 feet and 500 feet out on the line, or other means, to limit the incoming voltage to 2.5 times the crest value of the terminal arrester rating, a special arrester at the machine terminal to limit the voltage to the crest value of the machine high potential test, and a capacitor at the machine terminal to slope the wave front, thus limiting the turn-to-turn stresses. The capacitor also serves to limit internal overvoltages due to reflection at the neutral. For neutral grounded solidly or through resistance equal to or less than the combined surge impedance of the machine windings 0.1 μf capacitance is sufficient; while for isolated neutral, capacitance up to 0.5 μf may be necessary. Ground wires over the line for the initial 2,000 feet are recommended to protect against direct strokes.*

*For cases where the machine feeds the outgoing line through transformers, a special arrester is recommended at the machine terminals, to be connected in multiple with a capacitor, which in most cases may be 0.1 μf.*

* * * * *

## INTRODUCTION

THE behavior of traveling wave voltages in rotating a-c machines was discussed in two papers in 1930.[1,2] The principles of protection by means of arresters, capacitance and inductance were briefly outlined. In the ensuing two and a half years many of these principles have been studied further and some have been tried out in practise. It is the purpose of the present paper to present the results of certain of these studies and experiences and to offer a practical method for providing protection for rotating a-c machines against traveling wave voltages due to lightning.

The coordination schemes discussed in various papers at this convention are not generally applicable to rotating a-c machines, since the usual insulation used for this type of machine is of an entirely different order from the insulation of non-rotating apparatus, such as transformers, oil circuit breakers, bus bars, etc. A special treatment of the problem is necessary, therefore, to obtain a proper protective scheme.

## INSULATION CHARACTERISTICS OF ARMATURE WINDINGS

Rotating a-c machine insulation strength is influenced by the limitations of the dry type of insulation used, by space limitations, and by the types of insulation required to meet temperature and mechanical conditions.

These and other inherent characteristics of rotating machines make it difficult to incorporate high impulse strength in armature windings. Where transformers and similar apparatus are considered to have an impulse ratio in the general order of two or more, it appears that in view of the aforementioned factors, rotating machines should be considered to have an impulse ratio only slightly greater than unity. Thus, for the purpose of selecting protective equipment, safe practise will be adhered to by considering the crest value of the machine's one-minute high potential test voltage as the maximum value of impulse voltage which should be allowed on the coil or major insulation.‡

*Turn Insulation Impulse Strength.* The development of turn insulation of machines has been based on the normal voltage between turns and on operating experience. Under normal conditions, the turn insulation is subjected to relatively low voltages, ranging from 1 to 400 volts, but when a steep wave enters the winding, 100 to 1,000 times normal voltage may be impressed across the turns. Since it is not economical to insulate armature coil turns to withstand such steep wave voltages, and because it is feasible to protect the insulation normally in use, it appears rational to adhere to present insulation standards and to apply protective measures.

*Traveling Waves in Machine Windings.* It has been shown previously (reference 2) that an armature winding behaves similarly to an equivalent transmission line having a high surge impedance and a low propagation velocity. Fig. 1, based on tests on some medium and large machines, shows how the surge impedance and propagation velocity vary with rated terminal voltage. In the case of delta-connected or Y-ungrounded neutral machines, it is important to

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1. For references see end of paper.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

‡Armature windings have a one-minute test voltage whose crest value is equal to $\sqrt{2}\,(2e + 1{,}000)$ where $e$ is the rated terminal-to-terminal rms voltage. The maximum allowable impulse voltage therefore is equal approximately to $3e$ for machines whose ratings are above 4,000 volts. If $E$ is taken as the crest value of the machine's terminal-to-terminal rating, the maximum allowable impulse voltage for the machine will be approximately $2.12E$.

know the time required for waves to travel from the line terminal to the neutral or midpoint of the winding, depending on whether the machine is connected Y or delta. This time may be expressed in micro-seconds and is referred to as microseconds length. Fig. 2, shows how the machine length varies with rating.

### Fundamentals of Protection

The problem of protecting rotating a-c machines may be divided into two major parts:

(A) The protection of turn insulation.

(B) The protection of major or coil insulation.

*(A) Protection of Turn Insulation.*

When a voltage wave enters an armature winding, it requires a small but definite time to travel around a coil. The voltage, Fig. 3, which occurs between adjacent turns depends upon the steepness of the entering wave and the length of the coil. This voltage appears not only across the turn insulation, but across the tier insulation as well if the coil is wound in tiers. Strand insulation and one-turn coils are not affected by this voltage. The maximum rate of voltage change (wave front) which a coil will withstand, depends upon the turn insulation and the turn length.

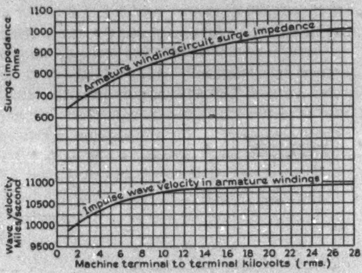

Fig. 1—Impulse Voltage Wave Characteristics of Medium and Large A-C Rotating Machines

It is obvious that by placing lumped capacitance to ground at the machine terminal, the capacitance will be charged through the surge impedance of the line by all waves arriving over the line (Fig. 3). The charging rate will depend upon the crest value of the incoming wave, the surge impedances of the line and machine, also the value of capacitance in microfarads. Knowing the characteristics of the machine and line, it becomes a relatively easy matter to determine the maximum rate of change (wave front) which can occur in the winding. Examination of a large number of machines indicates that in general 0.1 $\mu f$ (as a minimum) placed at the machine and with a limit placed on the applied wave, as will be given later, is sufficient to prevent excessive turn stresses. This criterion does not necessarily establish the total amount of capacitance which should be used at the machine, as it will be seen later that for other reasons a larger capacitance may be required.

This paper deals primarily with traveling wave voltages due to lightning. In some cases switching near the machine terminals may appreciably stress the turn insulation. This fact should be taken into consideration in applying the protection recommended.

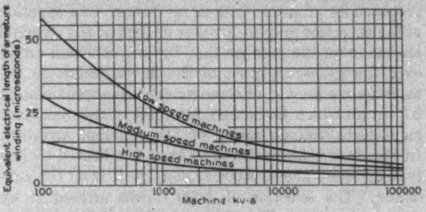

Fig. 2—Equivalent Electrical Length of Armature Windings of Medium Voltage A-C Machines

*(B) The Protection of Major or Coil Insulation.*

In general, the installations of machines in need of protection may be classified into two groups: first, machines directly connected to outgoing exposed feeders, and second, machines connected to exposed lines through transformers.

*1. Machines Directly Connected to Exposed Lines.* If a steep front long-tailed wave is allowed to enter the winding from directly connected exposed outgoing lines, the voltage-to-ground throughout the winding will depend on the machine connections. Fig. 4, shows voltages measured to ground on a 6,600-volt Y-connected machine when a ½-150 microsecond wave was applied to the machine over a line of 300 ohms surge impedance. It is to be noted that voltage to ground was measured for three conditions, namely; neutral grounded through a resistance equal to surge impedance of winding, neutral solidly grounded and neutral isolated. For the purpose of this study, the first two conditions may be grouped together. It follows, there-

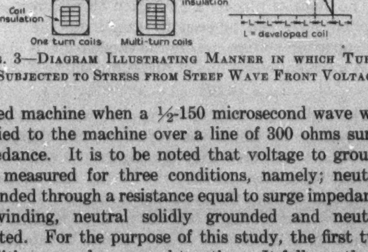

Fig. 3—Diagram Illustrating Manner in which Turns Are Subjected to Stress from Steep Wave Front Voltages

fore, that machines may be classified into two groups: (a) machines operating with their neutrals grounded (where the resistance at the neutral is equal to or less than the combined surge impedance of all windings), and (b) machines operating with their neutrals ungrounded ($R$ greater than $Z$), and delta-connected machines.

(*a*) *Grounded Neutral Machines.* The one-line diagram given in Fig. 5A shows the plan of protection proposed for grounded neutral machines. The selection of the capacitor and the arrester located at the terminal are made on the premise that the waves which arrive over the 2,000-ft section of the line adjacent to the machine are limited in some manner to approximately 2.5 $Ea$ (in which $Ea$ is the crest value of the maximum name-plate voltage rating of the terminal arrester). In Fig. 5A this limitation of voltage is indicated by line type arresters placed 2,000 ft and 500 ft from the generator. The selection of 2,000 ft was arrived at by theory and tests. This distance allows approximately 4 microseconds for the line arrester to operate before reflections from the capacitor reduce the incoming wave at the line arrester. This distance also makes it possible to utilize the surge impedance of the line between the line arrester and capacitor to obtain a charging rate for the capacitor.

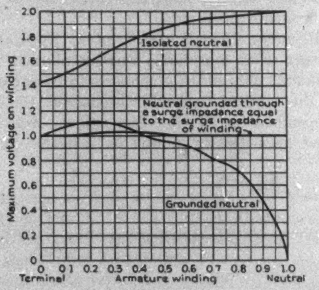

FIG. 4—MAXIMUM VOLTAGE-TO-GROUND ON A 6,600-VOLT Y-CONNECTED ARMATURE WINDING WHEN A 0.5/150-MICROSECOND IMPULSE WAVE IS APPLIED

The value of placing a limitation on the crest of the applied wave can be seen by examining the formula for capacitor voltage, where the capacitor $C$ is charged by a wave $E_1$ over a line of surge impedance $Z_1$.

$$e_c = 2E_1\left(1 - \epsilon^{-t/Z_1C}\right)$$

The higher the crest of the applied wave, the higher the voltage to which the capacitor will charge. It should also be noted that the higher the crest of the applied wave, the greater will be the rate of charge (steepness of wave front) on the capacitor. It follows, therefore, that placing a limitation on the applied wave is a matter of economics. Since the cost of capacitance increases approximately as the square of the voltage rating, it is apparent that for the higher voltages it is desirable to keep the required capacitance small.

Hence, for the higher voltage grounded neutral machines, it will be more economical to use small capacitance of the order of 0.1 $\mu$f (to prevent turn stress), in parallel with an arrester, which will limit the crest value of the entering wave below 2.12$E$, than to use large capacitance without the arrester in parallel. This type of protection can be used because no positive voltage reflections occur at the neutral when the neutral resistance is equal to or less than the combined surge impedance of the windings. For low-voltage machines, where the capacitor costs are not so high, the use of a large capacitor dispenses with the need of an arrester in parallel.

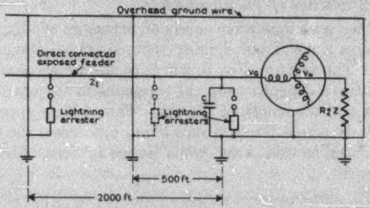

FIG. 5A—SCHEME OF PROTECTION FOR GROUNDED-NEUTRAL MACHINES

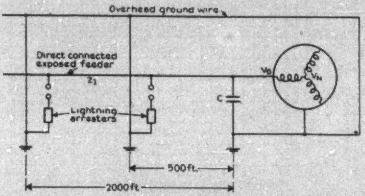

FIG. 5B—SCHEME OF PROTECTION FOR UNGROUNDED-NEUTRAL MACHINES

(*b*) *Non-Grounded Neutral or Delta-Connected Machines.* The problem of protecting ungrounded neutral (Fig. 5B), or delta-connected machines, is much more difficult than that of protecting machines whose neutrals are grounded. This is obvious when we consider that a machine winding may have a length of 50 microseconds and the reflection point for the waves may be 50 microseconds removed from the point of voltage limitation. It is also apparent that where the waves which enter the winding may reflect approximately to double value at the neutral, the entering voltage must be held at the line terminal to one-half the allowable machine impulse voltage (2.12$E$). The difficulty of this problem can further be appreciated when we consider the fact that the crest value of the operating voltage is $E$, and that in order to prevent positive reflections from exceeding the allowable impulse voltage, any device which is placed at the terminals to limit the incoming wave must hold the voltage to 1.06*E*.

Since our present day arresters cannot operate between such narrow voltage limits, some other means of obtaining lower impulse voltages must be used. It is apparent that by placing a limit on the impulse voltage which could reach the machine from the line, and by placing a sufficiently large lumped capacitance at the machine terminals to ground, the capacitance will act to reduce the impulse voltage.

For the purpose of calculating the value of this capacitance, it has been assumed that the average installation will consist of a double-circuit three-phase line, whose combined surge impedance is not less than 250 ohms per phase. It is further assumed that the voltage which is allowed to pass the line arresters over the 2,000-ft section adjacent to the machine is a 0/40 microsecond wave, whose crest value is 2.5*Ea* and that waves arrive simultaneously over each of the six conductors.

The 0/40 microsecond wave was selected as fairly representative of the most severe waves met in practise. The sheer front was chosen to simplify the calculations by eliminating one term from the equations.

Fig. 6 is a plot of the voltages which occur at the machine terminal and also at the isolated neutral for various values of capacitance at the machine terminals. These curves indicate that for the assumed set of conditions 0.5 $\mu$f will, in general, offer sufficient reduction in the voltage at the terminal to prevent overstressing the machine insulation throughout the winding. These assumed conditions apply to a single-circuit winding. If the machine has a multiple circuit winding or there are multiple machines, the voltage will be lower than indicated by the curves.

The exact determination of the capacitance required is more important from an economic standpoint in the case of machines which are in the 12- and 15-kv ratings, or higher, as these are the ratings at which capacitor costs are relatively high. It is obvious that the larger the capacitance in microfarads, the greater will be the margin of protection to the machine, and where a large capacitance can be obtained without substantial increase in cost, it is advisable to use larger capacitance.

It should be noted in this set of curves that the machine length is given in microseconds time required for voltage to traverse the windings, and that the curves are plotted for machines whose lengths *L* vary from 10 to 40 microseconds. For a given value of capacitance at the machine terminals, the resulting voltage at the neutral depends on the length of the winding up to a length where 100 per cent reflection of the entering wave occurs. Lengths greater than this would not increase the value of reflected voltage.

### OVERHEAD GROUND WIRES

It has been pointed out that the selection of the protective equipment located at the terminals of the machine is based on the assumption that the incoming surges are limited to 2.5*Ea* for a distance of at least 2,000 ft from the machine. In regions where direct strokes are frequent, overhead ground wires should be located over the 2,000-ft section of line. The effects

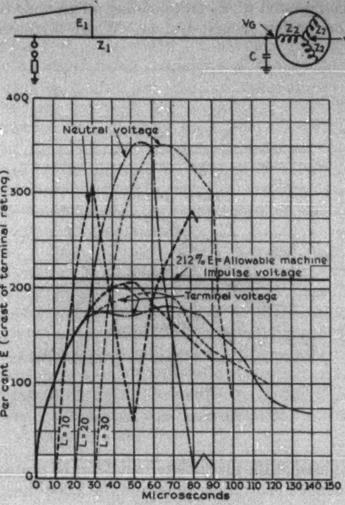

FIG. 6—A

VOLTAGES WHICH OCCUR AT MACHINE TERMINALS AND AT NEUTRAL OF AN ISOLATED-NEUTRAL MACHINE WITH A 0/40-MICROSECOND IMPULSE WAVE OF 2.5*Ea* ARRIVING AT THE MACHINE. MACHINE LENGTHS *L* VARYING FROM 10 TO 40 MICROSECONDS

$Z_1$ = 250 ohms, $Z_2$ = 800 ohms
$C$ = 0.12 $\mu$f

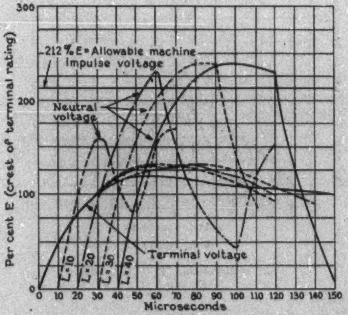

FIG. 6—B

$Z_1$ = 250 ohms, $Z_2$ = 800 ohms
$C$ = 0.3 $\mu$f

of arrester ground resistance can be largely overcome by connecting the arrester grounds, the capacitor grounds and the machine frames together with the overhead ground wires, and bonding all grounds to the common station ground system. Where a station arrester is used at the machine terminal for the protection of a grounded neutral machine, and the 2,000-ft section is protected by overhead ground wires, as suggested, it should not be necessary to install the line arrester at 500 ft from the generator (Fig. 5A).

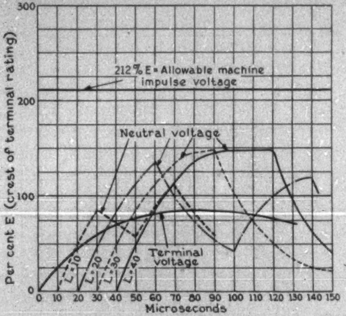

FIG. 6—C

$Z_1 = 500$ ohms, $Z_2 = 800$ ohms
$C = 0.3\ \mu f$

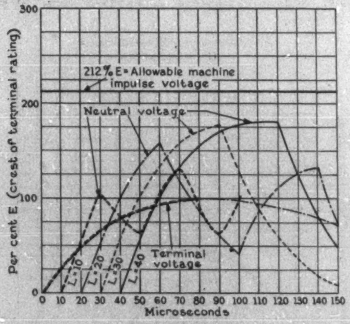

FIG. 6—D

$Z_1 = 250$ ohms, $Z_2 = 800$ ohms
$C = 0.5\ \mu f$

## INDUCTANCE AT MACHINE TERMINALS

It would be possible to remove the necessity for limiting the line voltage at approximately 2,000 ft out on the exposed lines, by inserting an inductance in series with the machine and placing a capacitor to ground between the machine and the inductance. It is necessary, however, to place an arrester on each side of the inductance to prevent the voltage resulting from oscillations between the lumped capacitance and the inductance from exceeding 2.12*E*. This plan has not proved practical up to the present time, and it seems that the alternative plan proposed has certain advantages which are applicable to the problem of protecting machines in general.

## PROTECTION OF MACHINES CONNECTED TO LINES THROUGH TRANSFORMERS

Messrs. Palueff and Hagenguth have shown the mechanism by which surges are transmitted through transformer windings.[3] Examination of their solution discloses that for YY-connected transformers with both neutrals grounded, the electromagnetic component of surge voltage which may be transmitted through to the machine windings should be dealt with by reducing the (upper) circuit shown in Fig. 7 to that shown below where *L* in henrys is obtained from the transformer short-circuit reactance as measured from the low-voltage side and the surge impedance of the line is reduced to its proper value, that is, by multiplying the surge impedance on the high voltage side by $\left(\frac{1}{r}\right)^2$, in which $r$ is the ratio of high-tension to low-tension turns.

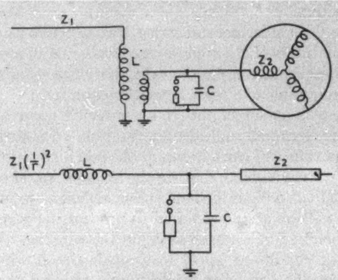

FIG. 7—PROTECTION OF MACHINES CONNECTED TO LINE THROUGH TRANSFORMERS

Upper—Actual circuit
Lower—Equivalent circuit

YY transformers with both neutrals grounded constitute the only connection for which the waves transmitted to the machine cause positive reflections of voltage at the machine neutral. Under these conditions sufficient capacitance must be used to prevent reflections at the isolated generator neutral from exceeding 2.12*E*. The voltage which may be transmitted through the transformer depends upon a number of factors, such as kilovoltamperes, reactance, ratio of transformation, etc., and it is therefore necessary to examine each case to determine the amount of capacitance required.

For all other transformer connections, the voltages due to the waves which are transmitted into the machine windings cancel when the waves arrive at the machine neutral, hence, for protection to the machine it is only necessary to limit the crest value of the entering waves and to prevent sudden voltage changes (steep waves) which would cause excessive turn stresses. Examination of a number of cases indicates that by placing 0.1 μf capacitance or more in parallel with the proper arrester between transformer and generator, this protection will be accomplished.

The capacitor which is placed in parallel with the arrester has two useful purposes: first, it aids in sloping off steep waves and, second, it reduces the crest value of the entering wave where the impressed wave is not of sufficient severity to charge the capacitor to the voltage required for arrester operation.

### CONCLUSIONS

This paper outlines a rational method of providing protection for rotating a-c machines from surge voltages caused by lightning and originating on exposed transmission lines.

Machine characteristics are indicated which influence the proper selection of protective equipment.

The plan of protection involves a limitation of the voltage of the applied wave to 2.5 times the maximum name-plate rating of the terminal arrester for a distance of at least 2,000 ft from the machine, and the use of special arresters and lumped capacitance at the machine. Capacitance of 0.1 to 0.5 μf may be necessary, depending on whether the machine neutral is grounded or isolated.

Overhead ground wires should be placed over the exposed line to a point at least 2,000 ft out from the station to protect this section of line against direct strokes.

Where the rotating machine is connected to the exposed line through a transformer, a special arrester and a capacitance of 0.1 microfarad or greater in parallel should be located between the transformer and machine.

Breakdown of machines is probably a progressive process and if the suggested protective means are not applied until the machine has been in operation for some years, the anticipated results may not be fully realized.

### ACKNOWLEDGMENT

The authors wish to acknowledge the valuable assistance of Mr. H. G. Brinton in the mathematical analysis connected with this problem and in the preparation of the appendix, which follows:

## Appendix

The voltage at the machine neutral was calculated by superimposing the original entering wave and the various reflections in their proper time relation. The first entering wave is completely reflected at the neutral and travels back to the terminal, where part passes out and part is reflected back into the machine with reversal of sign, and becomes what we may call the second entering wave. This wave enters $T$ seconds after the first wave, where $T$ is the time required for a wave to travel twice the length of the winding from terminal to neutral or point of complete reflection. In the same way there is a succession of entering waves at intervals of $T$ seconds, each being opposite in sign to the preceding one. Each wave produces double its voltage at the neutral or point of complete positive reflection, and the total voltage at that point is the sum of the voltages due to the several entering waves added at the proper time intervals.

The voltage at the machine terminal is also the superposition of a number of voltage waves impressed at intervals of $T$ seconds. However, these voltage waves are easily determined if we know the various entering waves. The first terminal voltage wave is equal to the first entering wave. The second terminal voltage wave is equal to the sum of the first and second entering waves (which are opposite in sign). The $n$th terminal voltage wave is the sum of the $n$th and the $(n-1)$ entering wave.

Thus, for the present purposes it is only necessary to obtain formulas for the various entering waves in order to determine the total voltage at the terminal and the neutral at a given instant. It is not necessary to take space for the derivations here.

To obtain the voltage waves for the several machine lengths examined, the various entering waves were first plotted and then added in their proper time relationship, depending on the length of machine assumed. The formulas follow:

$E = E_1 \epsilon^{-Bt}$ = wave on line
$B$ = 0.0173 for a 0/40 wave
$Z_1$ = surge impedance of incoming line
$Z_2$ = surge impedance of machine
$C$ = capacitance in microfarads at machine terminal
$L$ = time in microseconds required for a wave to travel the length of the machine winding
$V_G$ = voltage at machine terminal
$V_N$ = voltage at machine neutral
$V_{1e}, V_{2e}, V_{3e}$ = first, second, third entering waves
$t$ = microseconds from beginning of each wave.

Let

$$A = \frac{Z_1 + Z_2}{Z_1 Z_2 C}$$

$$K = -\frac{2}{B - A}$$

$$M = Z_1 C$$
$$D = Z_2 C$$

$$S = \left(\frac{K}{D} + 1\right)$$

$E_1 = 100$ per cent

$$V_{1e} = V_{1G} = \frac{K}{M}\left(\epsilon^{-At} - \epsilon^{-Bt}\right)$$

$$V_{2e} = -\frac{K}{M}\mathrm{S}\left(\epsilon^{-At} - \epsilon^{-Bt}\right) + \frac{2K}{M}\cdot\frac{t}{D}\epsilon^{-A}$$

$$V_{3e} = \frac{K}{M}\mathrm{S}^2\left(\epsilon^{-At} - \epsilon^{-Bt}\right)$$

$$-\frac{2K}{M}\left(1+\mathrm{S}\right)\frac{t}{D}\epsilon^{-At} + \frac{2K}{M}\frac{t^2}{D^2}\epsilon^{-At}$$

$$V_{4e} = -\frac{KS^3}{M}\left(\epsilon^{-At} - \epsilon^{-Bt}\right) + \frac{2K}{M}\left(1+\mathrm{S}+\mathrm{S}^2\right)\frac{t}{D}\epsilon^{-At}$$

$$-\frac{2K}{M}(2+\mathrm{S})\frac{t^2}{D^2}\epsilon^{-At} + \frac{4K}{M}\cdot\frac{t^3}{3D^3}\epsilon^{-At}$$

$$V_{5e} = \frac{KS^4}{M}\left(\epsilon^{-At} - \epsilon^{-Bt}\right) - \frac{2K}{M}\left(1+\mathrm{S}+\mathrm{S}^2+\mathrm{S}^3\right)\frac{t}{D}\epsilon^{-A}$$

$$+\frac{2K}{M}\left(3+2S+\mathrm{S}^2\right)\frac{t^2}{D^2}\epsilon^{-At}$$

$$-\frac{4K}{M}\left(3+S\right)\frac{t^3}{3D^3}\epsilon^{-At} + \frac{2K}{M}\cdot\frac{t^4}{3D^4}\epsilon^{-At}$$

Formulas for further entering waves, if desired, may be written out from inspection of the preceding formulas.

## References

1. *Effects of Lightning Voltages on Rotating Machines and the Methods of Protecting Against Them*, F. D. Fielder and Edward Beck, Trans. A.I.E.E., Vol. 49, Oct. 1930.

2. *Voltage Oscillations in Armature Windings under Lightning Impulses*, E. W. Boehne, Trans. A.I.E.E., Vol. 49, Oct. 1930.

3. *Effect of Transient Voltages on Power Transformer Design—IV*, K. K. Palueff and J. H. Hagenguth, Trans. A.I.E.E., Vol. 51, 1932.

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## Discussion

### PROGRESS REPORT ON IMPULSE TESTING OF COMMERCIAL TRANSFORMERS

(Vogel and Montsinger)

### FACTORS INFLUENCING THE INSULATION COORDINATION OF TRANSFORMERS

(F. J. Vogel)

### COORDINATION OF INSULATION

(Montsinger, Lloyd and Clem)

### IMPULSE VOLTAGE TESTING

(Harding and Sprague)

### PROTECTION OF ROTATING A-C MACHINES AGAINST TRAVELING WAVE VOLTAGES DUE TO LIGHTNING

(Rudge, Wieseman and Lewis)

**F. F. Brand:** The interesting time lag curves, given in Mr. Vogel's paper and more completely in the paper by Messrs. Montsinger, Lloyd and Clem, which show the relation of insulation and various gaps, are apt to give the impression that the whole scheme of insulation coordination which has been recommended by the A.I.E.E. Transformer Subcommittee is of little value, since the dielectric strength of the point gap which has been standardized increases more rapidly than that of solid insulation for very short time lags.

A careful consideration of the basis, on which coordination of insulation has been worked out, shows that one cannot form a general opinion merely from these time lag curves. Primarily coordination of insulation was started to form a basis for the relation of power transformer insulation to that of the rest of the circuit, for those transients which these transformers should be expected to withstand when connected to overhead circuits.

The time lag curve shown by Mr. Montsinger indicates that an insulation barrier, which has a 10 per cent margin of dielectric strength over a point gap of a given setting for wave fronts of 2 microseconds or more, will fail if a wave with a front of less than ¾ microsecond and of sufficient voltage to break the point gap is impressed on it.

Effective coordination implies a factor of safety in actual transformer insulation with which the transformer has not been credited in this curve.

Secondly, for power transformers at least, it is very doubtful if they will be subjected to waves of less than 1 microsecond front. The coordination point gap settings for these were worked out on the basis that they would be placed close to the transformer but interposed between it and the line over which the transients were expected to flow.

Any stroke on the line, whether induced or direct, which has a voltage of the order of the coordination gap breakdown is above the corona point of the line, and the wave front is therefore sloped by losses as the wave is propagated toward the station. In addition to this, the wave front on arriving at the station is sloped by the lumped capacitance of the station apparatus and connections.

It appears, therefore, that a wave front of ¾ microsecond or less, which the time lag curve shows might be dangerous to transformer insulation can appear only at the transformer terminals, not by reason of direct strokes on the line, but actually at transformer terminals unprotected from such strokes by grounded metal such as overhead ground wires, steel work, or direct stroke masts.

Furthermore, it appears that the rate of voltage rise in the rare event of a direct stroke striking the transformer terminals, due to the enormous voltage of the lightning stroke, would be such that any gap, even a few feet away, might not receive anything like the same voltage in a fraction of a microsecond as that received by the transformer terminal struck. The type of gap, therefore, might have little effect in preventing excessive voltage on the transformer in such cases. Good engineering practise would obviously seem to demand that valuable apparatus such as power transformers should be shielded effectively from direct strokes to their terminals.

**C. L. Fortescue:** The title of the impulse testing paper is very satisfactory. The writer feels that on such an important matter as the impulse testing of apparatus it was advisable to proceed with caution for the reason that while a great deal of data have been obtained during the past five years with regard to surges produced by lightning on transmission lines, there has not been time enough yet fully to digest these data.

There has been a tendency to treat the subject of coordination of insulation in apparatus and system as if it were an entirely new approach to the solution of the economic protection of power systems. For this reason suspicion might very well be created in the minds of some of our system engineers that the development of the principles of coordination might lead to the throttling of initiative in the design and layout of electrical systems. It is very vital that this impression be prevented.

In discussing the paper by Messrs. Montsinger, Lloyd and Clem the writer points out that it is possible to protect the transmission and connected substation so that the line surges resulting from lightning due to direct or induced strokes will be reduced at their source so that what enters the substation will relatively be innocuous.

It would seem logical for a system carefully laid out and well protected to use apparatus in the substation requiring a lower impulse test specification. It also seems logical that the manufacturer should have the privilege of recommending what class of insulation may be used with different levels of protection of line and station. Otherwise the principle of coordination (which I take to mean the application of sound engineering and economic principles to the protection and insulation of power systems so as to produce continuity of service at a minimum cost) would have no meaning.

There will naturally be some differences of opinion among transmission engineers as to the application of these principles especially in the case of 220-kv systems, some favoring the use of lightning arresters to maintain continuity of service by preventing spillover of the gap and others being in favor of using a higher level of insulation with correspondingly higher gap setting leaving out the arrester. I, myself, believe that the best protection and the one that insures continuity of service at all times will use an approved type of lightning arrester in multiple with the gap.

The subcommittee that has been working out the methods of carrying out impulse tests on transformers is to be congratulated in having developed a logical and satisfactory technique for carrying out such tests especially the ingenious method of applying power follow up, which insures that if any damage occurs to the transformer as a result of the application of the impulse it will show up positively.

Mr. Vogel's paper presents the results of a series of tests to determine the approximate impulse time lag characteristics of insulation of the type used in transformers. As he points out, these characteristics do not necessarily apply to an actual transformer because the impulse stresses in the transformer will depend upon its physical design, that is to say, whether the principles of coordination have been properly carried out in the insulation of the coils and coil groups in the transformer design. Where these principles have been properly carried out the impulse time lag characteristics of the transformer as a whole will closely approximate that of the major insulation as shown in Mr. Vogel's paper. The data given in Mr. Vogel's paper therefore are of great value to transformer manufacturers.

The data presented comparing surge strengths of insulators, gaps, bushings, and transformer major insulation are of great value. It is interesting to note how convenient these impulse time lag curves are as a basis of comparison between insulators having different impulse time lag characteristics. The writer is convinced that if the proposed basis of comparison of minimum flashover and puncture curves for different standard waves had been adopted the result would have caused a great deal of confusion. The impulse time lag curves are all the fundamental data needed for coordination and the use of the 1-5 and 1-10 waves should be confined to shop and laboratory investigations.

A critical examination of these impulse time lag curves at once suggests the advisability of obtaining a coordinating gap that has an impulse time lag characteristic corresponding more closely to that of the major insulation. This at once suggests the sphere gap with close spacing between spheres. Certainly transformers connected to systems unprotected by ground wires where direct strokes may occur close to the station should be coordinated for short time lags, however, if the proper type of lightning arrester always is used in multiple with the gap such coordination is satisfactorily obtained and the arrester does away with the possibility of flashover of the terminal.

It is interesting to note that the major insulation adopted for transformers in the past which met the requirements of the standard A.I.E.E. tests also met the requirements of coordination in the higher voltage classes. As discussed later these test specifications with the necessary insulation to meet them were obtained in the past as a result of experience with practically no knowledge as to the formation and propagation of surges due to lightning and it is surprising how well these tests met practical requirements in service. With the data now available and their further analysis and with the improvements in design and testing of power transformers we should look forward to a radical improvement in their operating performance in the future.

The paper by Messrs. Montsinger, Lloyd and Clem contains a great deal of valuable information in connection with the subject of coordination of the insulation of apparatus in substations to withstand the surges that enter the substation as a result of switching or lightning. One is tempted to ask what is meant by the term coordination as used in this connection. Certainly the opening paragraph of the paper attempts to define its meaning, but it seems inadequate. It seems that what is meant is nothing more than sound engineering in applying the data and knowledge that are available to obtain a layout that will give reliable service at the least possible cost. Coordination must be carried out therefore in such a way that flashover of coordination gaps is comparatively rare. One way to do this is to use lightning arresters to protect the gap against flashover, in which case the gap may be considered as back up protection to the arrester. Another way is to raise the insulation level of the whole station layout and protect against it at its source in the line by adequate ground wire protection.

In the past the knowledge and data that have been obtained in the last five years on lightning surges were not available, very little also was known as regards switching surges and even today we probably know less about switching surges than we do about those due to lightning. As a result the engineering of transmission lines substation and apparatus insulation was largely statistical. Lightning arresters were developed to a limited extent and no doubt played a part in protecting apparatus. Fortunately the impulse strength of the substation insulation of the early installation generally was below that of the line and apparatus so that the insulators performed the functions of a coordinating gap and usually saved the apparatus from failure. It is surprising how well the apparatus insulation arrived at by this rough and ready engineering has stood up in the past, in fact we are compelled to admit that there was some degree of coordination carried out between apparatus insulation and substation insulation even in those days when reliable data as to surge magnitude were lacking.

The principle of coordination should not be considered as applying solely to the station apparatus and its insulation level, which may be determined by a so-called coordinating gap, but extends nowadays to the whole system. Thus in the transmission line the overhead ground wire is the relief measure in coordination of the transmission line insulation, and the configuration of the ground wires with respect to the line wires must be such as to shield them effectively from an oncoming stroke and the distance between ground wire and line wire must be coordinated with the span length the surge impedance of tower and footing or buried counterpoise so as to prevent side flash. The line insulation and the clearance from towers under wind conditions must be coordinated. It may not be economic to design the line so as to be lightning proof, but it may be coordinated for a certain level of protection and sufficient data are now available to enable the designer to predict with reasonable accuracy the performance of a line designed for a given level of protection. The computations for determining the ground wire spacings and tower insulation clearance for a given level of protection are simple, all the necessary data having been systematized.

With respect to the protection of the station against direct strokes, the problem is simpler even than for the line, for the line runs over very rough territory where low footing resistances are difficult to obtain and spans are long and towers high. Recourse must then be had to a counterpoise connected to the tower footing and more liberal insulation and tower clearances all of which are expensive when long distances have to be considered. In the case of stations the area to be considered in connection with the overhead protective measures is comparatively small, the supporting structures are close together so that even when the resistivity of the earth is high a very effective ground can be obtained by a buried grid connecting all the support footings. The supporting structures need not be high and therefore the surge impedance will have a slight effect in raising the potential at the top of the ground wire support when struck. Since the structures are close together the potential at the middle of the ground wire span will be kept at a low value when struck so that the clearances between it and the bus structure need not be very great. In calculating the surge to which a transformer may be subjected as a result of a direct stroke at a ground wire between two supports, we must compute the potential at each point of the ground wire between supports during the duration of the stroke and consider the capacity coupling between line and ground wire between supports as the medium by which the surge on the ground wire is conveyed to the line and thereby to the transformer, the surge impedance of the line and the capacitance of the transformer are in multiple.

It will readily be seen that since the capacity of the transformer is large compared to the coupling capacity between supports in representative cases, a very small part of the potential of the ground wire appears across the terminal of the transformer, probably not enough to operate the arrester or coordinating gap. In the case of the transmission line itself when a ground wire is struck, provided the protection is effective, no surge will appear on the line though its potential will be raised at the point of stroke and will die out as the surge on the ground wire reaches successive adjacent towers; after the second or third tower the reduced potential is negligible. Even when the ground wire protection is inadequate the surge that appears on the line due to its failure is limited to waves of steep front chopped by the insulator of the line which alternates very rapidly as this travels along the line.

It is practicable therefore to protect a transmission system and connected stations so that the probability of a surge of sufficient magnitude entering the stations is very small, but it is nevertheless always advisable to install coordinating gaps. There are today some high voltage systems without lightning arresters which have been in operation in lightning territories for five years without experiencing spill-over due to lightning; which is a practical proof of the soundness of the above statement. This degree of protection may be justified economically on 220-kv systems and higher, but not so for 138-kv supplies and below, except for very special cases. For these low voltage systems lightning arresters as well as coordinating gaps should be used.

It is noted that in order to show the complete coordination between insulation, gaps, etc., volt-time curves on the 1½-40 wave on a common sheet have been used. This departure from the authors' former contention that coordination data should be presented in terms of several of different lengths and steepness such as the ½-5, 1-10 and 1½-40 is very gratifying, since the writer has always insisted that the impulse time lag characteristics are fundamental data and fully determine the coordination characteristic of every type of insulator. The impulse time lag curves presented were obtained by using the 1½-40 wave which is convenient since it has been adopted by the transformer committee for all tests on transformer. It would be advantageous if a wave as nearly perpendicular as possible could be used for impulse curves, for the reason that flashover on the front makes the impulse ratio higher than it should be and therefore exaggerates the steepness of the curve at the short time lags. Such a wave chopped at a suitable time would be quite as suitable as the ½-5 and the 1-10 wave and by adding resistance in series with the chopping gap can be made to duplicate these waves for all practical purposes. We have used impulse time lag curves to coordinate the insulator and clearances of towers for potentials that appear as the result of direct stroke and also checked them in the laboratory by artificial waves corresponding to these potentials; the results have tallied closely enough for practical purposes.

**F. W. Peek, Jr.:** A year ago the writer suggested that the Institute appoint a committee to formulate rules for impulse testing of transformers. The rapid progress that has been made is indicated by the papers presented. The writer made the suggestion at that time that "one of the most important problems in establishing lightning tests is to devise means for detecting incipient turn-to-turn, coil-to-coil or other failures. This is so because the operator must feel assured beyond any reasonable doubt that the transformer is as good after the test as before the test was made." This is true particularly if the windings can oscillate. It would be worth the committee's while to give considerable attention to this subject. As matters stand at present, it cannot be said that impulse testing is a very accurate measure of the worth of a transformer.

For example—assume that three different types of transformers ($A$, $B$, and $C$) are given impulse tests. Assume further that $A$ fails through the major insulation but that $B$ and $C$ apparently pass the test. It might well be that $B$ was damaged and that $C$ actually passed the test because it was properly designed. In this case the test without a detector is worse than useless. The real deciding factor still rests in the knowledge and experience of the designer in such matters. This, of course, also applies to 60-cycle testing, but fortunately this test is made over a sufficient interval of time so that, usually, damage can readily be determined. In fact, this can be done with great certainty by an instrument or detector called the "coronaphone"[1].

Impulse testing voltages should bear a definite relation to the voltages that are permitted upon transmission lines by the insulators, coordinating gaps and arresters. For practical purposes lightning voltages may be divided roughly into three classes: *direct strokes; traveling waves;* and *transients of internal origin such as switching surges.*

*Direct stroke voltages* for the purpose of this discussion are those that occur directly to the terminals of the apparatus and are most severe because they are exceedingly steep and may reach high values before the insulators or ordinary gaps have had a chance to spark over. The chance of strokes occurring directly to apparatus terminals is not great even when special protective means are not provided. Fortunately, by certain protective schemes direct stroke voltages, as defined above, may readily be prevented. In fact, most direct stroke voltages are converted into voltages of the traveling wave type before reaching apparatus.

The *traveling wave type of voltage* has a more sloping front than the *direct stroke type* and may be the result of induction; the residual of a direct stroke to the line left by insulator sparkovers a few hundred feet away; or a direct stroke near a station well protected by ground wires or lightning rods. Not all these voltages are true traveling waves but are included in this type because of their effects.

The *only important effect of voltages of internal origin* is on the setting of protective apparatus. Such apparatus must be adjusted so that voltages of this type are not continually causing sparkover.

There are several papers in this session that treat of the effect of coordination on transformer insulation. The following discussion is confined principally to the paper by Messrs. Montsinger, Lloyd and Clem because the data given on insulations are very complete and cover the whole range from switching surges to direct strokes.

An examination of Fig. 2 in this paper shows that insulation strength does not vary greatly until the time is decreased to about 2 μsec for the method used. This method is referred to later. The strength then begins to increase appreciably. The figure also shows that the coordinating rod gap likewise begins to increase rapidly at the 2 μsec point. Although both the insulation and the coordinating rod gap increase in strength with decreasing time, the sparkover voltage of the gap increases much more rapidly than the strength of the insulation. These characteristics show that the rod gap is quite ideal for the usual lightning voltage but that the margin decreases for the direct stroke type. Any desired margin can be maintained with the rod gap when ground wires or other protective means are used to reduce the direct stroke of voltage to the traveling wave type. An alternative scheme is to use a gap with characteristics of a sphere or to reduce the rod gap setting somewhat. It should be pointed out that Fig. 2 does not represent a transformer but shows the general characteristics of an insulation barrier. There is no constant impulse ratio or relation between 60-cycle and lightning voltages for transformers. The writer has observed many tests on all types of barriers and transformers. It is possible for a transformer to have sufficient margin to be quite satisfactory for rod gap coordination. These curves do not condemn the rod gap as a coordinating gap. Incidentally, it is of interest that Mr. Vogel's data are in agreement with those of Messrs. Montsinger, Lloyd and Clem up to 2 microseconds. Further comparison is not possible.

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[1] *General Electric Review*, January 1929, Vol. 32, No. 1, page 45.

It is pointed out that 2 microseconds does not represent a critical time interval when insulation characteristics suddenly change as Mr. Vogel suggests. The appearance of 2 microseconds as the point where characteristics change is brought about largely by the manner in which the tests are made. These tests were made by applying a 1½-40 wave at different voltages and noting the time at which failure occurred. At 2 microseconds the crest has practically been reached and a shift occurs from the tail to the front of the wave and the effective time interval thus becomes suddenly greatly reduced. There is a transition from tail sparkover to front sparkover. Thus, these are not true voltage time curves and are misleading. The effect of this type of test is equivalent to the ½-5 wave at approximately 1.5 microseconds point in Fig. 2.

It may be concluded from the above that the most effective protective system is: insulation levels as fixed by the coordinating rod gap values; protective means, largely in the way of ground wires extending at least a few poles out from the station or towers for converting the direct stroke voltages into the traveling wave type voltages; and lightning arresters. It may be desirable sometimes to add a gap of sphere gap characteristics, particularly where ground wires are not used.

**H. V. Putman:** There has been considerable misunderstanding on the part of some operating engineers regarding the work of the Transformer Subcommittee of which the writer is chairman. They have felt that the committee has been trying to tell them how they should establish insulation coordination in their substations, what level of insulation they should use on their lines, and what level of insulation they should require in their transformers. This is not the purpose of the committee at all. We feel that the general problem of insulation coordination largely is outside the scope of the committee's activities. The joint NEMA-NELA committee on insulation coordination is, we believe, the proper body to handle this broad, general problem of insulation coordination. It is only one small part of this problem affecting the transformer proper which we are endeavoring to handle, and even here we are not attempting to tell operating engineers how much or how little surge strength they should have in their transformers. We are endeavoring to bring order into our design procedure, to make it possible for a manufacturer to supply intelligently a transformer having specified impulse strength and to prove definitely that that impulse strength has been obtained.

Surely in carrying out any plan of insulation coordination which may finally be agreed upon, it will be necessary to know and prove the impulse strength of every piece of apparatus entering into the coordination scheme. The committee wants to remove any uncertainty regarding the impulse strength of transformers. It wants to know and prove the impulse strength of transformers so that they may intelligently be fitted into any scheme of coordination desired.

So far as our committee is concerned, operating engineers are perfectly free to choose the level of insulation which they desire in high voltage transformers. The writer has talked to some operating engineers who felt that certain transformers, because of the unusual importance of their application to continuity of service, should have higher impulse strength than normal, and that standards of at least two different values of impulse strength should be established for each voltage class. The writer is very sympathetic to this view, but it is a matter outside the scope of the subcommittee's activities.

It is true that the subcommittee has established a schedule of coordinating gaps for different voltage classes, but this has been done not to dictate apparatus or line insulation levels, but only to indicate or specify what impulse strength may reasonably be expected in well designed transformers meeting the existing A.I.E.E. tests. It is true also that in extending this schedule of coordinating gaps to the distribution circuit voltages in a manner consistent with the gaps established for the higher voltage classes, it became apparent immediately that the existing A.I.E.E. tests for these lower voltages were much too low and should be raised. Experience also had indicated the same thing and had brought about increases in the insulation actually employed by several manufacturers over and above that required by the A.I.E.E. tests. The subcommittee therefore is considering recommending the low frequency A.I.E.E. tests in these lower voltage classes be raised to make them consistent with the coordinating gaps which have been established and with field experience.

The schedule of coordinating gaps for the different voltage classes established by the subcommittee now extends from ¾ in. for the 600-volt class to 64 in. for the 220-kv class, and represents the best standard for insulation strength available today. Apparatus designed to test against these gaps in line with the subcommittee recommendations for impulse testing will meet the existing low frequency A.I.E.E. tests in the higher voltage classes and the proposed increased tests in the lower voltage classes. The writer personally recommends (not speaking for the subcommittee), that those who are engaged in this broader problem of insulation coordination accept the subcommittee schedule of coordinating gaps as the normal insulation level of transformers in the different voltage classes, and if it can be agreed that certain transformer applications, because of their relative importance, require higher or lower insulation than normal, then the insulation level and test be that corresponding to the next higher or lower gap in the schedule.

In conclusion reference is made particularly to the changing attitude of the industry toward the matter of impulse testing. When this problem was assigned to the subcommittee at the winter convention of 1932, grave doubts were expressed as to the feasibility of impulse testing. In one of the papers presented at that time, the statement was made that there was no way to detect damage due to impulse testing except by complete dismantling and examination of the insulation piece by piece. It is surprising to hear that same thought again voiced by Mr. Peek in his statement that the subcommittee has not arrived at any satisfactory solution to the detection problem. In the writer's discussion at the winter convention last year it was stated that impulse testing was practical and failures could be detected. These statements were based on the work of Mr. Vogel in developing impulse testing with dynamic power connected and with the surge synchronized with the crest of the voltage wave. Since then Mr. Vogel's work has been published and the subcommittee has adopted this method in its recommendation. The progress report of the subcommittee leaves little doubt about the feasibility of impulse testing, or little question about the matter of detection of failures.

If Mr. Peek actually does experience these pinhole failures which he and his associates have mentioned so often in connection with surge testing, there must be some peculiarity in his design practise which is responsible for this, because in our experience we have never found pinhole failures except as a secondary result of a major breakdown. We have always been able to detect any failure during the surge test by the method outlined in the concluding paragraph of the progress report of the subcommittee. But more important, every transformer in which no damage was detected by the proposed method, when torn down, was found to be absolutely clean—and we have looked for these pinhole failures with magnifying glasses.

It is certain that the method of detection proposed by the subcommittee will indicate any major insulation failure to ground, any failure between coils, any failure lengthwise of an entire group, and a streamer of appreciable magnitude. It would appear, therefore, that the problem of detecting insulation damage during surge testing has been solved in a manner satisfactory for all practical purposes.

In various conversations with operating engineers during the last 15 months, the writer has found several who were strongly opposed to impulse testing, fearing some damage to the insulation as a result of the test. But it was an interesting experience to see one operating engineer who was violently opposed to impulse testing, become one of its most ardent advocates. This change in attitude is, in a lesser degree, characteristic of the whole industry.

It was suggested last year that the subcommittee in undertaking this work should propose tests which would be relatively severe and not just some fireworks which might be fun to look at, but which wouldn't be significant. The tests which the subcommittee has recommended represent the consensus of opinion of the members in this matter of severity. They may or may not meet with general approval among the Institute members. While we desire to have a frank opinion from the members of the Institute regarding the recommended tests, it should be pointed out that we are working in a relatively new field. Our practical experience with commercial impulse testing is still limited. No field experience is now available on which to judge the adequacy of the proposed tests. But it would appear certain that the tests proposed would insure transformers of higher impulse strength than many now in service which have established excellent service records.

The writer would therefore bespeak a word of sympathy for the proposed outline of impulse tests and suggests that it be given a trial for a period of two or three years, at the end of which time we shall be in a much better position to know what changes should be made.

Mr. Vogel presents in his paper the fundamental data required to answer an important question which has occurred to all of us who have been studying the problem of insulation coordination: how much impulse strength can be obtained in a transformer designed to meet the existing A.I.E.E. low frequency tests? If we assume that the major insulation of the transformer is designed to meet this test with a proper margin, and if we assume further that the designer employs the necessary refinements (proper proportions, padding, elimination of creepage surfaces, shielding, etc.) to make the internal impulse strength, that is, between turns and coils, equal to that of the major insulation, how much impulse strength will be obtained in the transformer as a whole, and will this be sufficient to coordinate properly with present recommended gaps? Mr. Vogel's data indicate that in the higher voltage classes and down to the 34.5-kv class, internal coordination will be obtained both for long waves and for waves as short as 2 $\mu$sec, where the margin between the impulse strength of the insulation and the flashover voltage of the coordinating gap appears to be a minimum. This also will be true for both positive and negative waves. At the critical point of 2 microseconds, the margin of protection substantially is the same as that of the ultimate low frequency dielectric strength of the major insulation and the standard A.I.E.E. low frequency test voltage.

Below the 34.5-kv class, Mr. Vogel's data indicate again the necessity of raising the present standard A.I.E.E. tests and suggest values which would make them consistent with the recommended coordinating gaps. Mr. Vogel's paper makes a valuable contribution to the subject. He discloses for the first time the shape of the time lag curve for major insulation of transformers, its impulse ratio, and the nature and effectiveness of the internal coordination which will be obtained with gaps of the conventional type. I am glad he has confined his paper to this single problem, which is the paramount transformer problem of interest to those engineers who are shaping the industry's recommendations in this matter of insulation coordination. Best of all, the paper establishes from fundamental data the reasonableness of the recommended coordinating gaps and constitutes the best possible argument for their acceptance by the industry as the normal level of surge strength for the various voltage classes.

The paper by Messrs. Montsinger, Lloyd and Clem contains much valuable information and presents the results of a large number of tests on the impulse flashover values of insulator strings and gaps under a variety of conditions. It is regretted that the laboratories of Mr. Montsinger's company and of the writer's company do not agree fully as yet on all of these test results.

The authors emphasize the care and precautions necessary in this test work and point to agreement between the Schenectady and Pittsfield laboratories to substantiate the correctness of their results. We also emphasize the care necessary in making measurements of this kind and point with equal pride to agreement of results between our Trafford laboratory and our high voltage laboratory at Sharon. These laboratories are manned by independent groups of men working with quite different apparatus, yet their results agree very closely. I suspect that the source of the difference between Westinghouse and General Electric results will be found not in a lack of care on the part of either, but more likely in some difference in the fundamental standards employed by the two groups and on which their measurements must in the final analysis depend.

In spite of our laboratory differences at the present moment, there is one thought which I would like to leave with the utility engineers who will be using the results in working out their coordination problems. This thought, with which I believe the authors of the paper will agree is that the laboratory work involved in securing the kind of data presented by the authors and which will be presented by my associate is really an enormous job, and it has been carried on by our two companies at considerable expense. I feel that these laboratory groups, therefore, have rendered and are rendering the industry a great service—one which should be appreciated—because after all, this fundamental work is absolutely necessary to the successful conquest of lightning disturbances; necessary to a still closer approach to the goal of perfect continuity of electric service. I hope, therefore, that the attitude of the utility engineers toward these laboratory groups may be one of patience until they can remove their differences. In presenting our results and methods of measurement thus openly, we hope that out of the discussion may come some clue as to the cause of our differences, which may be helpful in overcoming them.

The statement in the paper that the gap is considered as a device for setting a maximum to the voltage which may be applied to the station apparatus, may be misleading to those less familiar with the subject, because the gap does not actually do this at all, as the authors well know. What the gap does do is to chop the wave. If low enough in magnitude, the wave is chopped on the tail, so in this case the wave is limited in length, not in magnitude. If the surge is high enough, the gap chops it on the front—not at any particular maximum value, but to a value depending on the steepness of the front. This is the factual interpretation of the function limiting the maximum voltage which can reach the apparatus.

The statement that the gap is not a protective device because it offers no relief from repeated applications of surges up to its flashover value seems to me meaningless. To claim that the gap is not a protective device is justified only if it is admitted that the transformer is not fully protected by it—that the transformer needs additional protection against repeated surges over the gap or of less than its flashover value. We design our transformers so that they are amply protected by the gap alone if proper ground wire protection against direct strokes over the substation is provided.

In regard to protection against direct strokes, I believe it is too early to claim that a sphere gap would protect effectively. It will provide, as Mr. Vogel points out in his paper, greater margin between the transformer insulation strength and its flashover voltage for very short time lags than the ordinary gap. But the steepness of the wave front of a direct stroke is very great—no one knows how great—and with waves of extremely steep front, even the sphere gap has a pronounced time lag, so the degree of protection would be somewhat uncertain at best.

Last year at the convention I reported on a commercial test which we had made on a 42,000-kva, 220-kv transformer using a wave front of 11,000,000 volts per microsecond, which was the nearest thing to a direct stroke that we could produce in the laboratory. This wave front was three times as steep as any recorded in the field, but Mr. Fortescue stated at the time that he believed a direct stroke to the bushing would even be very much steeper than that. Very little is known about the flashovers of gaps and bushings or the insulation strength of windings when subjected to these extremely steep wave fronts. It appears doubtful that we shall ever depend on insulation coordination for protection against these extremely steep waves. The best protection against direct strokes is effective ground wire protection over the substation and out onto the line at least for a short distance. This kind of protection properly designed can be depended on fully.

In connection with the proper location of protective gaps, Mr. Bellaschi has made a suggestion to improve the protection against very steep surges, which is discussed in the following. When a gap flashes over due to a very steep front surge it chops it on the front and passes on to the transformer an impulse of very high voltage of very short duration. If the gap is located right at the transformer it will experience the full voltage of this impulse, but if the gap is located at some little distance from the transformer, this impulse in approaching the transformer will have both the steepness of its front and the magnitude of its crest appreciably reduced due to the capacity of the transformer and adjacent apparatus and structure, thus subjecting the insulation to a much less severe stress. This is a very practical method of sloping off the front and suggests that perhaps the best place for the gap is not right at the apparatus but at some little distance from it, particularly if there are ground wires over the substation to prevent direct strokes to the apparatus. Better still, two gaps might be used, one at the apparatus and one at some distance away.

The authors of the paper suggest a level of impulse strength for bushings 15 per cent above that of the protective gap. We are in agreement that the bushing level approximately should be of this order. If this level is accepted, the degree of protection afforded the winding by the bushing can appreciably be increased and internal coordination made more effective. It is important that the impulse flashover of bushings be standardized rather than the 60-cycle dry flashover values, which are of no significance from an operating standpoint. In view of these facts, the proposed standard for 60-cycle dry flashover values for bushings which was submitted to the Electrical Standards Committee a year and one-half ago, when less progress had been made on insulation coordination, should be recalled and revised to establish impulse flashover values in place of dry 60-cycle values. There is no *positive* assurance that the desirable impulse values can be obtained with the present proposed 60-cycle dry flashover values. But it is only the impulse values and the wet 60-cycle flashovers that are of importance from an operating standpoint, or for the purpose of establishing a standard.

This subject was discussed by the Electrical Machinery Committee and it was recommended that the Transformer Subcommittee initiate some action looking toward a modification of this proposed bushing standard to substitute surge voltage values in place of the dry 60-cycle flashover values.

**H. K. Sels:** Referring to the several papers dealing with the insulation coordination of power transformers, it apparently still is the practise to consider the strength of transformer insulation in terms of a rod coordinating gap although a great deal of progress has been made with voltage measurements. If it is necessary to continue expressing insulation strengths with gaps, it might infinitely be better to return to a sphere gap standard that more nearly approximates the insulation volt-time curve. To carry this a step further, if we can use spheres, why not voltage and time directly?

From an operating standpoint, the use of a coordinating gap for protective purposes in a station is undesirable on account of tripouts. In order to prevent tripouts, some kind of lightning arrester equipment is necessary. Below are tabulated the voltages permitted at the terminals of present day arresters with test waves expressed in terms of a rod coordinating gap at 12 microseconds as compared with the proposed coordinating gap for power transformers.

| Voltage class | Transformer coordinating gap, in. | Arrester crest voltage gap, in. |
|---|---|---|
| 13,800 | 4.25 | 2.6 |
| 23,000 | 6.25 | 4.7 |
| 34,500 | 9.25 | 7.3 |
| 46,000 | 12.25 | 10.5 |
| 69,000 | 18.75 | 17.0 |
| 92,000 | 25.0 | 23.0 |
| 115,000 | 31.5 | 29.5 |
| 138,000 | 38.25 | 36.0 |
| 161,000 | 44.5 | 42.0 |
| 196,000 | 54.5 | 51.0 |
| 230,000 | 64.0 | 60.25 |

Since the arrester crest voltage is practically flat with time and transformer insulation has a much flatter volt-time characteristic than the coordinating gap, the necessity of expressing all measurements directly in voltage is emphasized by the small protective margin indicated by gap spacing alone.

Also, remembering that the protective value given above for the arrester is at its terminals without any allowance for impedance drops in the arrester and equipment leads and ground resistance, if any, there is some question whether the insulations proposed are sufficiently high. This is further emphasized by the recent trends to higher line, bus and bushing insulations.

Early agreement should be reached in expressing insulation characteristics by cathode ray oscillograms so that proper insulation levels may be selected by joint insulation coordination committees.

**Philip Sporn:** The report by Messrs. Vogel and Montsinger is a step in advance to put the question of transformer insulation and the entire problem of insulation coordination on a more rational basis. It cannot, however, be pointed out too strongly that almost everything recommended should be taken as a tentative recommendation, and that in many cases there is no question but that ultimate practise, when it is finally developed, is bound to be considerably different from that recommended here. Further, there is a great deal that still remains to be done to put the technique of impulse testing of commercial transformers on a sound commercial basis. This is true, for example, with regard to recommendations that tests be confined to the positive wave. While this may give a more severe stress to the transformer insulation, it is quite likely that coordination based on positive waves only will be entirely misleading and give a very poor and possibly dangerous setup under certain operating conditions. Again, the authors have apparently elected to slur over the very important question of determining whether or not any damage short of breakdown occurs to any portions of the windings in the process of impulse testing. It is apparent that this is too important to be left to chance. All these things, however, will come with time.

The paper does offer a basis of getting started and getting together some data and information on a method of testing that would sufficiently be close among all the groups following it so the data taken at various points later can be analyzed and interpreted with a view of making recommendations based on much fuller information than any that is available at the present time.

There are three points in Mr. Vogel's paper that are discussed in the following:

1. The statement that the average time lag curve of the major insulation of transformers is the same whether for positive or negative waves is not only not in agreement with the claims made by Messrs. Montsinger, Lloyd and Clem, but the data that Mr. Vogel furnishes are most certainly not conclusive or adequate to back up the claim. If the points presented in Fig. 9 give all the data, it certainly is far from conclusive as to variation of breakdown between plus or minus waves.

2. The claim, that coordination based upon present A.I.E.E. 60-cycle tests at operating voltages of 34.5 kv and above shows that the 60-cycle test requirements are satisfactory for coordination purposes, is contrary to experience cited before the Institute on several occasions, in which it was shown that equipment so insulated gave unsatisfactory operating results both with and without lightning arresters, and regardless of whether any coordinating gaps were present or not. It would seem as if great care ought to be taken in this regard before arriving at any definite conclusions.

3. A recommendation is made that a gap used should be protected by lightning arresters to obtain continuity of service. There is, of course, nothing new in this recommendation, this having been made many years ago. Here again, however, it ought to be pointed out that much data have been cited before the Institute in which attempts were made to prove the economic justification of lightning arresters, and that so far no data have been obtained that would justify it one way or the other.

Referring to Messrs. Montsinger, Lloyd and Clem's paper, the following points definitely call for comment:

1. The claim is made that nothing is gained by increasing the flashover of any part of the station equipment over that of any other part of the station. It would be very difficult for those familiar with the havoc wrought in a station or substation, upon occurrence of a short circuit of the bus itself, to agree with the authors. Further, if by the expenditure of a very modest sum, a short circuit can be kept away from the bus proper, then such an expenditure will be found economically worth while and will invariably be made.

2. It is stated that experience indicates that with modern arresters, gap flashovers are of rare occurrence. So far as I am aware, no such experience has been cited to the Institute or in any publication. It might be well for the authors to cite specific experience as a basis for their conclusions.

3. The claim is made that a cable itself is more or less a protective device. It would be interesting if the authors would furnish some information as to the length of cable necessary before the cable can really become a protective device, and whether in their opinion lengths of that order make it an economical protective device.

4. In Table V there is given a series of six different combinations of rod gaps, sphere gaps, lightning arresters, and capacitors for the protection against traveling waves. I would like to suggest to the authors a seventh combination in which no lightning arresters, capacitors, or gaps of any kind are employed, but in which a proper amount of insulation, possibly more than that required by A.I.E.E. standards, is used, where the only protective feature taken advantage of is the flashover characteristic of the bushing, that is, the protection the bushing gives the transformer as a protective gap. This particular combination has been employed a great many years and has worked very successfully and economically.

5. The recommendations with regard to gap spacing as a means of coordination have again the weakness in them pointed out several times before, and that is, since the insulation strength is a matter of volts and time, it might be well to coordinate in those terms. There does not appear to be any real reason why a primary unit like a volt should be shied at. A great deal of clarification of the entire problem ought to result if insulation strengths for any voltage are expressed in volts. The advantages claimed for the gap, based upon the fact that it will simplify the problem of coordination among the manufacturers, until such time as the various laboratories can iron out their differences, will disappear if the laboratories will agree upon and follow the recommendations with regard to insulation testing made by the Lightning and Insulator Subcommittee. Representatives of at least 4 laboratories have agreed that the procedure recommended is very practical and can be followed with advantage by all.

**F. J. Vogel:** In the paper by Messrs. Montsinger, Lloyd and Clem, there are many points of interest, and it is desired to emphasize some of those of greatest practical importance.

It is interesting to see that the authors have found that solid insulations have similar volt-time characteristics as the combination of fullerboard and oil ducts which they tested. I have found this likewise to be true except for the impulse ratio. As an example of this, I would cite the case of varnished cambric tape, as in cable insulation. For such a condition, a certain thickness has a one-minute strength of 100 kv, rms, or 141-kv crest. Its minimum surge strength is 230 kv, giving an impulse ratio of 1.63. This fact that different solid materials have quite different dielectric strengths is another reason why surge tests are essential to prove that transformers have the surge strength required regardless of their 60-cycle strength.

In Fig. 2, we find that the sphere gap has appreciable time lag characteristics, and we are glad that the authors have not only been able to determine that it exists, as we have previously, but to measure it and provide an accurate time lag curve. It is presumed that the voltage measurements were made quantitatively by sphere gap, since that is the Pittsfield standard of measurement. However, if the standard sphere gap also has a time lag, how can one be sure as to the accuracy of the measurements? If a divider is relied upon, I can well appreciate the care necessary to measure the time and voltage at such short lags, as a divider to serve this purpose must have a very high degree of fidelity. It is a pleasure, nevertheless, to see the authors' agreement with data taken by my associates in so far as the general shape of the curve for insulation in oil is concerned. However, it is to be noted that the data have been obtained from a single type of barrier not representative of high voltage transformer construction, and upon a relatively thin one. It appears therefore to me a bit rash to draw conclusions as to the relative positions at very short time lags of the various elements for all constructions and voltage classes. It similarly appears rash from a single series of tests and possibly random values on a few sample coil stacks to arrive at an impulse factor of 2.35. In other tests, values that high have been found, but to be conservative, the lowest values should be given the most weight.

Fig. 3 shows a generalized curve, but caution should be used in its application inasmuch as these relationships are different for the different voltage classes. Nevertheless, we agree that extremely high, short surge tests are most severe, as was brought out in Mr. Putman's paper[2] at the winter convention in 1932. At that time Mr. Palueff thought this not very severe due to the extremely short duration of the surge.

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[2] *Surge-Proof Transformers*, by H. V. Putman, A.I.E.E. Trans., Sept 1932, p. 579.

There is a limit for the short-time protection of any transformer, and therefore perfect coordination for direct strokes of lightning is perhaps not possible. Mathematically, from the shape of the curves, for shorter and shorter time lags, the impulse ratios of all elements approach infinity, and infinity over infinity is rather an indeterminate ratio to use to determine a factor of safety. In simple language, this means that ground wire protection should be provided over stations and adjacent lines to furnish protection from direct strokes if they are feared.

The point has been missed in discussing the use of sphere gap characteristics for protection, that the lightning arrester is a factor. The best combination is a protective gap which is just protected by the arrester. At least for autovalve arresters, the plain sphere gap is the best arrangement without the addition of point gaps. Suitable characteristics are obtained from the Torok tube, multiple spheres in series and other electrode arrangements, so that either the added protection or a further degree of economy could be obtained if any station designer saw fit to require it. From Table IV, it is seen that the ordinary sphere gap is rather impractical due to its size.

From Table V, it might be inferred that the use of the sphere gap as a protective means made the transformer proof against direct stroke. I fear this is somewhat optimistic, since in the extremely short surge given to the transformer, described in Mr. Putman's paper of last year, simultaneous flashover of bushing, 64-inch gap and sphere gap set at 2,000,000 volts occurred. It seems to us to be a little uncertain that protection against direct strokes can be obtained on such meager data, even though it is fairly safe to gamble on due to the rarity of such an occurrence.

The terms "outdoor" and "indoor" seem less expressive than "exposed" and "unexposed" to lightning surges. It is true that much apparatus commonly inside substations has not been insulated up to the standard for outdoor apparatus, as it was not considered to be exposed to the surges entering from outside lines. I doubt if it is safe to set up levels for unexposed apparatus at this time, but it might be desirable to set up such limits for instrument transformers and the like.

In the paper the value of 4 inches is proposed for 13,800 volts instead of 4¼, as approved by the Transformer Subcommittee. Is this an error?

Referring to Fig. 4, the purpose of curve *D* is not clearly given. It is understood that curve *C* is proposed as a standard level for all bushings in the future. If this understanding is correct, this would seem to be in agreement with the proposal in my paper. In this paper, 10 per cent is given as a proposed value but it is realized that very close limits are difficult to obtain and the 15 per cent figure given seems reasonable. The author, however, does not state the purpose of the special bushings for power transformers.

It is believed that curve *D* is given for two purposes: first, to state a belief in the desirability of a larger factor of safety on large units, and second, to reflect past practise. The writer does not quite see the justification for curve *D* on the basis of an increased factor of safety for the power transformers, since smaller transformers may be connected to the same circuits, not to mention instrument transformers and rotating apparatus. Therefore it does not seem to us justifiable to maintain a higher factor of safety for any one class of apparatus.

Practises with different manufacturers with regard to the levels used in the past have varied, although it is not questioned that most power transformer bushings have been at a level approximately that of the special bushings for power transformers given. It should be noted that transformers coordinated with these bushings should have windings insulated in excess of the standard tests. It is our belief that it would be desirable to lower these values for future design except as specifically requested to the contrary for any given installation. If additional creepage surface is required on account of dirt or other operating conditions, it would be recommended that the bushings be gapped to the lower level.

It has been suggested that all bushings should be made oversize so that they can be gapped. By this procedure, the atmospheric corrections in surge testing can be taken care of by increasing the length of the test gap to suit, and bushings made to give the exact performance desired. It is not believed that this is a reasonable proposition, because of the following: first, atmospheric corrections can be made by correcting the surge voltage applied; second, it would result in an increase in size of the higher voltage bushings as well as the lower; third, many operators believe that bushing gaps are unsatisfactory.

**V. M. Montsinger:** Mr. Vogel's work confirms a claim which I have made during the past 5 or 6 years namely, that the 60-cycle strength of insulation (major insulation in a transformer) bears a definite relation to the impulse strength. In other words, the 60-cycle strength at any given point within a transformer winding is a rough measure of the impulse strength or *vice versa.* It should be kept in mind, however, that this definite relationship applies only to the major insulations; that is, to the insulations between two different windings or from a winding to ground, unless the impulse voltage distribution is kept uniform and in the same order of proportion from ground throughout the winding as the 60-cycle distribution. Thus in a winding which is perfectly shielded, the induced voltage test will equally well demonstrate its ability to withstand a given impulse voltage. For an unshielded winding the ratio of low frequency to impulse strength must be confined to the major insulation adjacent to the terminals.

The value of the impulse ratio of 2.2 checks quite closely the value of 2.35 given in our paper on "Coordination of Insulation." I have used 2.35 since 1927. Some of this difference of 7 per cent can be ascribed, no doubt, to the fact that Mr. Vogel's impulse kilovolt values are slightly lower than Pittsfield values. An easy rule to remember is that the major insulation impulse strength is 3.1 or 3.3 times the 60-cycle kv effective strength, depending on which impulse ratio value is used.

With reference to the statement in the paper that the insulation time-lag curve is nearest the point gap time-lag curve at 2 microseconds the results of my tests in Fig. 2 and Table III of the paper on *Coordination of Insulation* show that the insulation curve will cross the gap curve for short waves in the order of ¾ to 0.8 $\mu$sec and remain below for all shorter waves, assuming that the insulation strength is 10 per cent above the gap strength at approximately 2 $\mu$sec. Whether or not these curves cross is rather difficult to determine merely by comparing volt-time curves, due to the fact that the insulation test points are quite scattered—some points even indicating that the curves may not cross. The fact that they do cross, however, can definitely be demonstrated by making tests on insulation and a gap in parallel, which tests show that to give equal protection to the insulation the gap spacing must continually be decreased as the impulse front wave becomes steeper and steeper. This is well illustrated in Table III, which shows that while a 20.5-in. gap represents the impulse breakdown of a given insulation barrier for a full 1½-40 wave, a 10.5-in. gap represents the barrier strength when applying 3.5 times the minimum wave necessary to flash over the 20.5-in. gap. With 5 times the applied voltage and with a very steep front (zero resistance in series with generator) the equivalent gap was only 6.25 in. This seems to establish beyond any doubt the fact that unless there is a very large margin between the insulation strength and gap strength for the full wave flashover of the gap, the curves will cross for very short waves.

In connection with the proposal to increase the 60-cycle test on transformers of 23-kv rating and below I agree that these test values should be increased because practise has demanded more insulation than the test indicated. I do not agree, however, to the exact values that Mr. Vogel proposes because with a slight modification the test values can be expressed by a simple formula expressed in terms of the rated circuit voltage. Furthermore, the values derived in the same manner and based on Pittsfield impulse flashover of the proposed gaps are somewhat different being 20.3, 27.3, 35.7 and 51 kv instead of 21.6, 29.2, 37 and 48.5 kv as derived by Mr. Vogel. This question should be referred to the Transformer Subcommittee.

**Edward Beck:** This discussion pertains to the paper by Messrs. Montsinger, Lloyd and Clem.

The writer is in hearty agreement with the authors' remarks regarding the undesirability of more than one insulation level for apparatus in a station. The logical coordination is believed to be the establishment of a reliable coordinating level by means of lightning arresters or gaps located at several points if necessary. If the station insulation is then set at some level above this with adequate margin, coordination is secured. The pyramiding of insulations in a station operates against standardization, increases cost, and appears to be unwarranted if a reliable low level is established.

The coordinating gap is not a protective device as it usually is thought of, for its operation is closely allied to a flashover. Although the gap prevents flashover of insulation of greater strength than itself, nearby, its operation produces outages. The modern lightning arrester operates without these outages. In the laboratory a lightning arrester in parallel with a coordinating gap of the same voltage class protects it against flashover, and service experience has indicated that the probability of a gap operation in parallel with an arrester is remote. It is characteristic of valve arresters that they will attempt to drain as much surge current as is necessary to limit the voltage across the arrester terminals.

The authors recommend the use of gap combinations which will furnish a coordinating device with flatter impulse characteristics than those now recommended. We would point out that the modern valve type arrester possesses to a considerable degree these desirable characteristics and appears, therefore, a desirable medium for coordination. Discussions of insulation coordination should not leave the lightning arrester out of the picture. In order to obtain a flat gap the authors propose the use of rod gaps and sphere gaps in parallel or of combinations with capacitors. Why go to such complications? The sphere gaps must be protected from the weather if they are to maintain their characteristics. A gap of this type for a 138-kv class circuit for instance, would be no small matter, as will appear from Table IV of the paper. If gaps of flat characteristics are demanded in addition to the lightning arrester, it would appear to the writer more practical to use gaps of the type patented by Allcutt some years ago and used on Westinghouse electrolytic arresters, or other gaps designed to have flat characteristics which do not demand the space required by sphere gaps and are not subject to the damage which a sphere gap suffers when it flashes over. Experiments indicate that gaps with these characteristics can be built if they are found necessary.

The authors propose the use of gaps as measuring standards. It is the writer's opinion that this is not desirable. A behavior of gaps is dependent on numerous external factors which may vary from time to time and vary between laboratories. We believe that an attempt to use a gap as a standard will cause more complications than already exist in the coordination programs. The use of gaps in comparing the performance of devices whose characteristics are as radically different as the flashover of an insulator and the terminal voltage across a lightning arrester would be unsound.

It is our opinion that coordination should be based on kilovolt measured by means of the cathode ray oscillograph, which in the hands of competent operators is more reliable than measurements made by means of gaps that are likely to be affected by many factors difficult to control. The difficulties which had to be wrestled with in attempts to study the performance characteristics of lightning arresters before the DuFour cathode ray oscillograph was introduced into this country by Messrs. Goodwin and McEachron are easily recalled from memory. Let us not go backwards. If there is disagreement between laboratories, let these be ironed out rather than seek a temporary expedient in gaps.

**F. D. Fielder:** The paper by Messrs. Montsinger, Lloyd and Clem is discussed from a laboratory standpoint, since similar data have been secured at our Trafford Laboratory. It is noteworthy that much of the data are substantially in agreement, although there are certain cases where the discrepancies are large.

The determination of precise humidity correction factors for surge tests is difficult because of the many variables that must constantly be under control. At Trafford a room with special humidity control is employed for these tests. The majority of points are obtained at a constant temperature of about 100 deg F with an absolute humidity range from 2 to 15 grains per cubic foot; these are also checked at low humidities at normal room temperatures. These tests have indicated slightly different humidity correction factors for suspension insulators and air gaps, as indicated in the following table:

MINIMUM SURGE FLASHOVER VALUES: POSITIVE WAVES
Variation in per cent of the standard (6.5 grains) voltages

| Apparatus | 1-5 microsecond waves | 1.5-40 microsecond waves |
|---|---|---|
| Insulators | 1.0 % per grains/cu ft | 1.8 % per grains/cu ft |
| Standard gaps | 1.2 % per grains/cu ft | 2.4 % per grains/cu ft |
| Values from "Coordination of Insulation" | 1.25 % per grains/cu ft | 2.33 % per grains/cu ft |

The insulator values in the above table are averages from 1 to 10 grains per cubic foot, the usual testing range, in which the variation with humidity appears to be uniform. Although these differences are negligible compared to the present variation in some of the reported surge values, they might become appreciable in certain cases of close coordination. It seems evident that the data given in Figs. 7 and 9 are insufficient to warrant any but general approximations to the humidity correction factors. In Fig. 7, for the 0.5-5 microsecond waves at least, horizontal lines will fit the points fully as well as those shown. More complete and more significant data are required for the determination of correction factors.

The question is raised as to whether any check has been made on negative wave correction factors; since the flashover data in other curves of the paper are corrected to standard conditions, it appears that the same correction factors were used. A study of negative wave humidity correction factors has been scheduled at the Trafford Laboratory.

From Table VI of the paper, the conclusion is drawn that rain has little influence on surge values. This table is misleading and the conclusions are inaccurate because the water temperature for the test was so low. For the air gap the voltages average lower than for standard conditions, mainly because the absolute humidity was lower than standard. (Saturated air at 45 deg F is equivalent to 3.4 grains per cubic foot.) The other factor influencing the flashover value is the relative air density, which in the case given causes flashovers higher than normal because of the low temperature. If warmer water were used in these tests, approximating normal thunderstorm conditions more closely, it would be found that the air gap flashover values would increase fairly in line with the absolute humidity. Insulators, on the other hand, appear to have lower flashover values with rain, whether the water is cold or warm. It is these conflicting trends which occur simply as a result of normal rainfall that make coordination within close limits somewhat difficult. Fortunately the effects of humidity, and to a certain extent of relative air density, become less pronounced with either short time lags or with waves with short tails.

The authors of the paper have persistently recommended the use of the sphere gap for measuring impulse voltages, and have presented much data secured in this manner. It is not apparent, nor hardly possible, that their time lag curves as shown in Fig. 2 could be obtained in this manner. Rather, the time lag curve shown in Fig. 2 for a sphere gap offers convincing evidence against the use of sphere gaps for the measurement of surge voltages.

We do not recommend sphere gaps for measuring surge voltages, but instead the cathode ray oscillograph. In the first place, the sphere gap alone shows nothing but the crest value of the wave, while the oscillograph shows the whole: the rate of rise, the crest value, the rate of fall, and the time lag. In the second place, the sphere gap is misleading, often incorrect, unless used in conjunction with an oscillograph, for the wave shape is of great importance. Before satisfactory results are possible with sphere gaps, it is first necessary to secure and prove accuracy of the oscillograph and divider system for the waves used, for otherwise the actual wave shapes are unknown. Since the oscillograph must be proved accurate before sphere gaps are employed, its use might as well be continued. In the third place, many of the sphere gap calibration curves are calculated or taken from 60-cycle curves and have not been proved experimentally correct for surge tests. Before sphere gaps should be used for general surge measurements they should carefully be calibrated with surges by acceptable test methods.

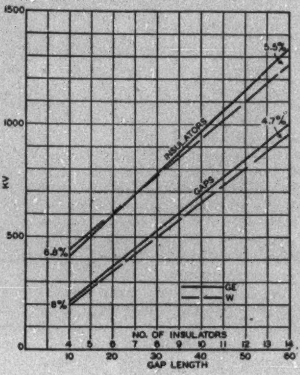


FIG. 1—COMPARISON LABORATORY RESULTS—1 ½/40 + WAVE

**A. C. Monteith:** The paper by Messrs. Montsinger, Lloyd and Clem accepts standards equivalent to those of the Lightning and Insulator Subcommittee for humidity; namely, 6.5 grains per cubic foot. The Westinghouse Company has been using this as standard in coordination work also, but some data recently obtained from the United States Weather Bureau indicate that previous to and during a storm absolute humidities as high as 9.5 grains have been recorded. Since the flashover of gaps, insulators, and bushings increase with humidity and transformer insulation is not affected by change in humidity it would appear from these data that the flashover should be considered at 9.5 grains for substation coordination work. The data obtained from the Weather Bureau also indicate minimum absolute humidities of 6.2 grains for eight storms tabulated. Where conservativeness in flashover values is desired, such as for line design, it is believed that 6.5 grains is a good value to use.

The authors have suggested the use of equivalent point gap spacings to express the impulse strength of various insulating structures, on the basis that this would eliminate corrections for humidity and air density and simplify the coordination problem. They have suggested an average gap spacing for the different waves to express insulator impulse strengths with a spread of 10 per cent in the lengths of gaps obtained. It is believed that this is complicated and for insulators, making use of average gap lengths, it is subject to differences of the same order of magnitude as actual kilovolt values obtained from different laboratories.

Test results on point gaps and insulators obtained from Westinghouse Laboratories as compared to the data presented by the authors, are shown in Fig. 1 for the 1½-40 wave and Fig. 2 for the ½-5 wave or 1-5 wave. It is seen that there is very close agreement with the 1½-40 wave while with the shorter wave, differences as great as 24 per cent exist. On insulators the differences are 11 to 17.8 per cent for the numbers of units shown. Equivalent gap lengths for expressing impulse strength of standard suspension insulators are shown in Fig. 3. It is seen that the spread in results from the two laboratories for gaps established at 6.5 grains is from 18.6 per cent to 10 per cent. The Westinghouse tests for humidity correction on medium and long gaps and insulator strings indicate that there is 0.6 per cent per grain higher correction for gaps than for insulators, in the range encountered in testing. If equivalent gaps are established in one laboratory at 1.5 grains and in the other at 6.5 grains (a possible range in testing conditions) an additional spread of 3 per cent would be introduced. These errors are as great as shown in Fig. 2.

Even using different gap lengths for different waves would introduce differences of larger magnitude than exist in kilovolt results based on the 1½-40 wave and differences at short string lengths approaching those of Fig. 2, for the 1/5 wave.

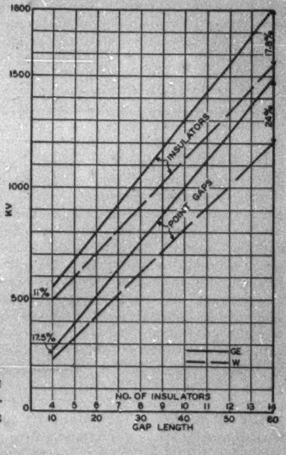


FIG. 2—COMPARISON LABORATORY RESULTS 1½/5 + WAVE

When all insulating structures used in a substation design, together with protective equipment are considered, the coordination becomes more complicated and more so if equivalent gaps are used. Fig. 4 shows relative volt-time curves for different types of apparatus in the substation. It is evident from an inspection of the gap curve compared to the others that when 10 per cent steps are considered for coordination purposes that an average gap could only be used for insulators. The complete picture for each piece of equipment would only be given by a gap length for each wave or time lag. If, as suggested by the authors, a voltage curve were established at the present time for the coordinating gap, the curves of Figs. 1 and 2 would be given by the two laboratories considered, with differences as high as 24 per cent. The only way the station designers could coordinate the various insulating and protective devices from different manufacturers would be to use a consistent base curve. The curve from either laboratory could be correct but the flashover level might be misleading if the wrong one were selected. Even if a consistent base curve were used with a gap length for each wave, still differences of 15 per cent could exist on insulators and there is no reason to believe that the differences for other apparatus would be less. Tests would establish the last point but it would be expensive and a burden to the laboratories with already heavy schedules, the personnel of which is spending all its available time trying to reconcile fundamental differences in measurements.

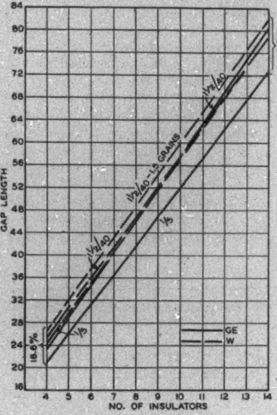


FIG. 3—SUSPENSION INSULATORS IN EQUIVALENT GAP LENGTH

It would appear better to recognize that there are laboratory differences, as has been done in the past, and until they can be eliminated compare the results from the different laboratories, put in a correction to put them on a common basis and coordinate with kilovolt values which the authors agree is the most desirable and fundamental. This still would be subject to the criticism of not knowing definitely what the flashover level was but it would allow using a yardstick which was a familiar engineering measurement. It would eliminate inaccuracies of different gap lengths from manufacturers for the same equipment on the same wave.

It is believed therefore that better results would be obtained by using corrections in kilovolt values. Gaps, it is believed, would complicate a subject already becoming involved and would result in differences due to varying test conditions.

**K. B. McEachron:** The writer pointed out in a discussion[3] of the paper by Montsinger and Dann, presented at the summer convention in 1930, that the use of a single gap was the best method of establishing a level of insulation, because such a gap could be protected by a lightning arrester near by, thus preventing interruptions to service. It was also pointed out that such a gap should be welcomed by the manufacturers and users of lightning arresters, as it gave a measure of both the arresters' performance and the strength of the transformer in service.

Subsequent experience has borne out the position taken in 1930 and today the principle of coordination is laid down along the lines above indicated. However, the problem does not appear today to be completely solved by the use of the simple rod or point gap as a coordination gap. It is shown in the Montsinger, Lloyd and Clem paper that insulation as used in the transformer does not exhibit the degree of time lag in its breakdown which is shown by oil or air. Thus it is not permissible to protect such insulation by a lightning arrester which has high time lag in its breakdown, if steep waves as from direct strokes are to be allowed to reach the installation. This illustrates one of the important advantages of the thyrite station arrester whose compensated gap has a flat breakdown characteristic.

In establishing the coordination gap it is desirable to use a gap having volt-time characteristics parallel with the insulation failure curve. The paper explains how this may be done, approximately by the use of the sphere gap in parallel with the rod gap. Although the setting of the rod gap, used alone, can be decreased until the proper ratio to transformer strength is secured for the steepest waves as with direct strokes, yet such a method reduces the 60-cycle and slow impulse flashover in like proportion which reduces the margin between the arrester and the gap unnecessarily. Since by far the great majority of disturbances reaching the arrester are not direct strokes close to the station, any unnecessary reduction of margin between the arrester and the gap should be avoided.

It is important to make clear that the volt-time characteristic of the arrester and the insulation should substantially be parallel at all wave fronts. The coordination gap should have a volt-time characteristic parallel to that of the insulation thus retaining the highest practical value for slow waves. With such a coordination the arrester will always protect the gap and the gap will always bear a correct relation to the strength of the transformer. Thus the transformer is protected and outages avoided.

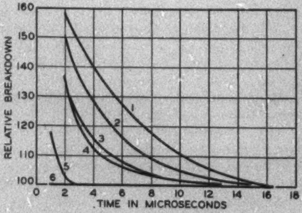
Arresters are not designed to withstand direct strokes of the greatest possible magnitude, but they will perform properly at currents which correspond to the weaker direct strokes. The use of a gap having the matched characteristic mentioned before would act to make the combination of arrester and gap safe for all kinds of direct strokes, although an outage might occur if the gap should function.

With extremely steep waves short distances may account for considerable voltages which is a fact requiring consideration. If 5,000 kv per microsecond is taken as typical of severe direct strokes then a potential of 5 kv per foot of conductor will be found, which may be doubled if reflections can occur. Thus if a gap is set for a potential of 500 kv less than the flashover of a bushing a distance of only 100 ft would be required to allow flashover of the bushing. This distance would be reduced to but 50 ft if a reflection to double potential took place.

FIG. 4—COMPARATIVE SHAPES—VOLT-TIME CURVES

1. Bushing
2. Pillar insulator
3. Point gap
4. Standard suspension insulator
5. Major transmission insulator
6. Crest autovalve arrester

100 per cent = 760 kv



It is not difficult to see, therefore, that large stations covering considerable territory cannot properly be coordinated with respect to direct strokes unless the gaps are relatively close to the transformers and the arresters must also be close by. It is better in case considerable distances are involved to keep the direct strokes off the station by overhead shielding conductors. If the overhead ground wires are extended out from the station so that the incoming front is sloped the potential per foot of conductor is decreased and distance between the transformer and the protective equipment becomes of less importance.

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[3] A.I.E.E. TRANS., Vol. 49, Oct. 1930, p. 1506.

The following is a discussion of the paper by Messrs. Rudge, Wieseman and Lewis:

It has been proposed that lightning arresters or their equivalent might be used between the neutral of the Y-connected generator and ground for preventing reflections at the neutral. If reflections at the neutral could be prevented, arresters at the terminals of the machine could, according to the paper, hold the voltage to a value of $2.12E$ and protect the major insulation successfully. To do this, however, requires that there be no positive reflection at the neutral. This means that the neutral must either be grounded through a resistance equal or less than the combined surge impedance of the windings discharging into the neutral ground resistance or it must be a capacitor of sufficient capacitance to prevent its being charged to a potential equal to the strength of the winding for any length wave which the generator may receive from its connected circuits.

On account of telephone interference the use of capacitance in the neutral does not appear to be a satisfactory solution to this problem. Because of the fact that during a fault in which one phase may be grounded it is necessary that a neutral resistor, if used, have sufficient current carrying capacity to prevent its failure during the time such a fault may exist. On account of circulating current and for other reasons it usually is undesirable to ground more than one generator in a station even if grounded through a resistance equal to the surge impedance of the windings of the machine.

On account of the possibility of faults occurring on one phase and also to avoid the operation of the generator with neutrals continuously grounded, the use of a material like thyrite has been suggested as a neutral resistor. However, any material having characteristics like thyrite is not suitable, for the following reason:

The dimensions of the thyrite would be so arranged as to provide a resistance equal to the surge impedance when the current flowing to ground was equal to the traveling wave currents expected through the machine. For all other currents less than this the resistance would be greater than the surge impedance of the machine and a positive reflection would take place. A lightning arrester connected in the neutral would perform in a similar manner in that up to the time that the arrester began to function a positive reflection would take place, which when reflected back through the windings toward the terminals of the machine would superimpose on the increasing voltage of the tail of the wave so that the potential somewhere between the line terminal and the neutral would exceed the strength of the machine.

This is well illustrated by an example; assuming that the terminal arrester holds the voltage to $2.12E$ and that the neutral arrester is so designed that it holds the voltage to $E$, a wave entering the machine having a front sloped as required to prevent turn stresses would have its crest voltage limited to $2.12E$. When the beginning of the wave reached the neutral arrester it would reflect just as though no arrester were present until a voltage of $\frac{1}{2}E$ in the traveling wave had been reached, which would be sufficient to cause the arrester to go into operation. If the arrester's resistance were less than the surge impedance no further reflection in the positive direction would take place. However, the original wave up to $\frac{1}{2}E$ allowed by the arrester would travel back through the windings of the machine and add to the incoming wave of $2.12E$, allowing a value of $2.62E$ to be impressed on the major insulation of the machine. This would stress the machine beyond its strength.

Calculations indicate that any device connected in the neutral which is connected into circuit through the operation of a gap would impose severe turn stresses on the machine at the neutral because of the sudden decrease in potential when such a gap sparked over.

The best method, therefore, of preventing reflections at the neutral in the light of present knowledge appears to be the use of a capacitor connected at the terminal of the machine having sufficient capacitance so that the wave is sloped sufficiently to prevent the application of voltages higher than the machine strength as the result of neutral reflection.

**E. D. Treanor:** The papers by Messrs. Montsinger, Clem and Lloyd, and Mr. Vogel present much more fully than has hitherto been done the behavior of insulation and rod gaps with reference to waves of different shapes and magnitudes. Messrs. Montsinger, Clem and Lloyd's paper particularly shows the unfortunate characteristics of simple rod gaps in the short-time range for use as measuring or coordinating devices. The great advantages of the rod gap for such purposes are its simplicity and ease of duplication, and these advantages may make it difficult to improve on the rod gap for these purposes.

However, the failure of the rod gap characteristic curve to parallel the corresponding insulation breakdown curve raises the question as to whether the Transformer Subcommittee's tentative recommendations for impulse testing require modification by the addition of a test wave of steeper front than the 1½-40 wave already suggested, or if only one wave is desirable, whether it should be of a very steep front or be a compromise between the proposed standard and a wave in the region of very short fronts.

This difficulty of making choice of one or more test waves which would satisfactorily demonstrate the strength of the transformer would largely be obviated by the use of a gap with approximately level characteristics, such as the combination of rod and sphere gaps described by Messrs. Montsinger, Clem and Lloyd. This is only one form of gap with such characteristics. Others are, at least, theoretically available. With such a gap, the problem so far as testing goes is very much simplified. Any convenient wave in the range that has been explored would be satisfactory and its standardization could be based on convenience to produce, ease and certainty of measurement, etc. The effect on the internal insulation of transformers of steeper wave fronts would have to be considered, but so far as the major insulation is concerned, the variation in magnitude of total stress will be much reduced.

Of even greater importance would be such characteristics in gaps used as coordinating devices to insure that a proper margin would be maintained in service between apparatus of a given strength and waves which can reach the apparatus over the lines. While a number of waves having fronts of an order to make rod gaps with recommended settings ineffective and maintaining this satisfactory margin may be, and probably is, very small, the question of reducing rod gap settings so that they will provide a proper margin against waves of the order of direct strokes has already been raised. While it may be some time before we have precise knowledge of the characteristics of direct strokes, there are some indications that the rate of rise may not be very much more severe than the waves now capable of production in the laboratory.

If a simple rod gap be reduced in setting far enough to leave a margin against even these steepest artificial waves, its use would be hampered by the resulting numerous flashovers from long waves of slow front and low magnitude or even switching surges.

Such use of rod gaps with low settings has been suggested. A gap with flat characteristics under similar conditions would determine coordination under practically all waves and facilitate the use of arresters having similar flat characteristics.

**J. K. Hodnette:** Messrs. Harding and Sprague have presented data based on laboratory tests to support the conclusion that the interconnection of lightning arrester and distribution service grounds results in improved protection of distribution transformers from lightning over the standard method of connecting the arresters between the primary leads and earth. This subject was discussed at length at the 1932 winter convention and has now generally been accepted. It limits the surge voltage between the primary terminals and the secondary neutral which for modern transformers is much less than the insulation strength of the windings.

The interconnection, however, cannot be made universally but is limited in its application. The surge current is discharged through the neutral service grounds, so that the interconnection cannot be made where the neutral is not grounded. It is not applicable to three-phase installations having delta-connected secondaries for supplying three-phase or motor loads for to do so would subject the connected apparatus to excessive surge voltages.

Where the transformer tank and core remain at some intermediate potential between that of the primary and secondary windings during the discharge of the surge current the transformers will be protected, although the potential of both the primary and secondary winding may rise to a high value above ground. However, if the tank is free to acquire some different potential, particularly in the case of an accidental ground maintaining the tank at or near ground potential, the difference in potential may become excessive and a flashover of one of the windings result. The same is true for transformers mounted on metal or conducting poles unless precautions are taken to connect the tank and the arrester and service grounds together. Therefore, in order to insure complete protection, it is necessary to take the tank into consideration and properly to coordinate or limit the potential between the tank and windings.

The interconnection between the lightning arrester and secondary service grounds should be limited to cases where there is a number of dependable service grounds of low resistance connected in parallel. It is not recommended where the ground resistances are high. This is emphasized by the fact that past experience has indicated that lightning arresters occasionally become leaky or short circuit, and if such arresters are interconnected with the secondary service grounds, primary current will flow to ground over the secondary service conductors. If the ground resistance is not low to start with, it may materially be increased through the drying out effect of the leakage current with the result that primary potential will be impressed on the secondary service lines for a considerable period of time or until the circuit is interrupted. In case the arrester is connected on the line side of the transformer fuse, the current will continue to flow until the feeder breaker is opened.

As a safety measure the lightning arrester should always be connected between the fuse and the transformer where the interconnection is used.

The flow of dynamic leakage current can be prevented by interposing a gap insulated for primary voltage between the lightning arrester ground connector and the secondary neutral, and without affecting the efficiency of the protection against lightning.

**A. M. Opsahl:** The writer believes that Messrs. Harding and Sprague have been mislead in one of their conclusions. They state that the voltage on the primary neutral as illustrated in Fig. 9B is due to a failure in the primary winding. This is not necessarily true. There is no discontinuity in the voltage wave to show a spark in such a failure. The voltage impressed on the primary phase wire is represented in Fig. 4. This surge after being transmitted through the primary winding to the primary neutral would have the modified shape shown in Fig. 7 with the somewhat higher voltage due to reflection. These values are determined by the effective transformer primary reactance and capacitance. The authors do not state the kva ratings of the transformers used. If a load such as the neutral line wire, or an equivalent 250 or 500 ohms to ground were connected to $H_2$ the voltage from $H_2$ to ground would be greatly modified. A secondary load will have an effect in decreasing the effective primary reactance.

**C. L. Fortescue:** The following is a discussion of the paper by Messrs. Harding and Sprague:

The results of the lightning investigations carried out by two of the leading manufacturers jointly with some of the electrical utilities during the past five or six years has given the electrical industry a vast amount of data on lightning and surges on transmission and distribution lines due to lightning. The technical analysis of these data has reached a state of development such that the performance of high-voltage transmission lines when subjected to direct strokes of lightning can be predicted with a reasonable degree of accuracy. New transmission lines designed and constructed according to principles deduced from the analysis of these data have been built and their performance has more than come up to the expectation of their promoters. The overhead ground-wire protection for the line has been extended to substations and with the advances made in the art as a result of these investigations, for a well protected high-voltage system, the likelihood of surges of extreme steepness and crest value entering the substation has been reduced to a negligible quantity. Practically such high surges as occur will arise from direct strokes in close proximity to the station, and then only in the remote possibility with proper coordination will failure of the overhead ground wire protection of the station result.

While not economically justified except for transmission voltages of 220 kv and above, it appears to be technically feasible to build a line that is lightning proof. Our engineers have assisted in the design of lines which have been in service in severe lightning territory for several years without a single outage.

The development of surge testing apparatus and the technique of surge testing has kept up fully with the increase of knowledge of lightning phenomena, and while the several large lightning laboratories which have been cooperating to secure reliable data on impulse strength of bushings, pillars, coordinating gaps, etc., have not been able to reach perfect agreement for short time lags it is expected that it will not be long before they do.

The increased knowledge of lightning phenomena on transmission lines and development of the technique of surge testing, have proved definitely that the danger to electrical apparatus insulation does not arise from the surges of normal operation nor from overvoltages of normal frequency which last for considerable time, but are due entirely to lightning surges, most of which last only a few microseconds. Therefore, surge testing of electrical apparatus is indicated as the logical procedure to determine those suitable for service. The question of test procedure and proper test values to determine whether all parts of the apparatus are coordinated properly is in the hands of the different subcommittees of the Apparatus Committee of the A.I.E.E. and also of the joint NEMA-NELA Committee on Coordination of Insulation.

The discrepancies which Professor Harding mentions in his paper between the coordination characteristics of different makes of surge-proof transformers will in the course of time undoubtedly be ironed out. Manufacturers of electrical equipment will be compelled to provide themselves with surge testing equipment or run the risk of losing out in competition with those who are equipped, for it is practically impossible to carry out the research and development necessary to produce properly coordinated insulation in electrical apparatus without the use of such equipment. Several manufacturers of electrical equipment have taken advantage of the fact that we have developed such equipment to a high state of perfection and have purchased outfits from us. One large utility has purchased one and we expect more to follow. The policy of the company with which the writer is associated is to encourage the carrying out of surge testing by utility engineers, for the more of this that is done, the sooner will the manufacturers appreciate the requirements that their apparatus must fulfill and the sooner will competition be placed on a sound basis.

While we do not have any standard surge test our practise in testing surge-proof distribution transformers is to carry out the surge-test with normal 60-cycle voltage on the transformer. Our surge-proof distribution transformer has been subjected to repeated tests of extreme severity under these conditions representing a great many years operating service, without the slighest sign of weakening of the insulation. Surges have been applied up to 1,500,000 volts without any damage to the insulation.

Table I in the writer's opinion does not mean very much, it only indicates the value of the surge that the arresters or protective device permit across the various parts of the transformer. Distribution type arresters have become well standardized and this is indicated in Table I, transformers 1, 2, 3, 4, 5 and 7. In No. 6 the impulse flashover of the protective device used is higher than for the distribution arrester, but the surge potential permitted by the protective device may be well within the safety limit of the insulation.

We have known for some time that there is a great variation in the bushing flashover of different makes of transformers. It is desirable to provide a bushing with fairly high flashover but the impulse strength of the bushing should be coordinated with that of the insulation, so that in an unprotected transformer bushing flashover will take place outside the case, protecting the internal insulation from failure. In Table II transformers *A*, *B*, *C*, and *D* were not properly coordinated, otherwise insulation puncture would not have taken place.

**D. W. Roper:** In a discussion in 1927 with engineers of the Electric Service Supplies, General Electric, and Westinghouse Electric and Manufacturing Companies, it was recommended that the Commonwealth Edison Company make a trial installation of interconnecting the ground wires of lightning arresters and the grounded neutral main of the secondaries of the 4-kv overhead distribution system. Subsequently, in order to determine what the effects of such an interconnection would be on the voltages on the customer's wiring at the time of lightning discharges, arrangements were made by the Utilities Research Commission to have tests conducted at Purdue University. The test results indicated that there was no hazard created on the customer's premises by the interconnection; and the interconnection was recommended in a paper[4] of a year ago by Messrs. Harding and Sprague and also in their present paper.

In order to check the effect of the interconnection the Commonwealth Edison Company installed 3,000 interconnections early in 1932 in blocks where the overhead gangs had other work, so that the locations were scattered well over the city. As only one lightning arrester per phase wire is installed in each block, the number of transformers affected was about 5,700, or about 17 per cent of the total.

The records for the year 1932 indicate that a reduction of over 60 per cent in transformer troubles (fuses blown and transformers burned out) due to lightning is secured by this interconnection. The records also indicate that in the average year, the total number of transformer troubles due to lightning in Chicago will be less than 5 per one-thousand transformers per year.

It happens, however, that this interconnection is prohibited by the National Electrical Safety Code and by the rules of the Illinois Commerce Commission. Permission was obtained from the Commission to make these interconnections with the proviso that they would be made only at those locations where, in addition to two driven grounds on the secondary neutral wire, the neutral wires of two services were grounded to water pipes on the premises of customers, and with the further proviso that we were to report all adverse incidents in connection with these installations. No such adverse incidents due to this interconnection have been noted to date.

As recorded in the *Electrical World* for December 24, 1932, Messrs. Haines and Corney reported a considerable reduction in lightning troubles on a similar trial installation of 777 transformers without a single case of trouble with the customers' wiring or meters.

In view of this favorable report on two field trials of the interconnection between the lightning arrester ground wire and the grounded secondary neutral wire, and in view of the recommendations for the interconnection, it is recommended that the Institute use its good offices to secure such changes in the National Electrical Safety Code as will permit this interconnection under proper safeguards.

**L. V. Bewley:** Messrs. Rudge, Weiseman and Lewis propose a protective layout consisting of four principal elements:

1. An overhead ground wire extending out from the station for 2,000 ft or more, and intended as major defense against direct strokes occurring within that distance of the station.
2. Line type arresters at 2,000 ft, and perhaps also at 500 ft from the station, to limit the crest of surges having their origin beyond the ground wire section.
3. Station arrester to limit the voltage applied to the machine winding (in the case of effectively grounded neutral machine).
4. Terminal capacitors to retard the wave front entering the winding so as to keep the gradients within safe limits; and to limit the crest of waves entering isolated neutral windings.

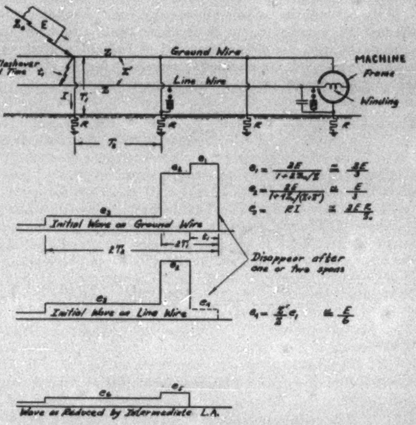
$Z_0$
E
Flashover at Time $t_1$
Z
Z'
Z
Ground Wire
Line Wire
I
$T_1$
R
R
R
R
$T_2$
MACHINE
Frame
Winding
$e_1$
$e_2$
$e_3$
Initial Wave on Ground Wire
$t_1$
$2T_1$
$2T_2$
$e_1 = \frac{2E}{1+2Z_0/Z} \cong \frac{2E}{3}$
$e_2 = \frac{2E}{1+2Z_0/(Z+Z')} \cong \frac{E}{3}$
$e_3 = RI \cong \frac{2ER}{Z_0}$
Disappear after one or two spans
$e_2$
$e_3$
$e_4$
Initial Wave on Line Wire
$e_4 = \frac{Z'}{Z} e_1 \cong \frac{E}{6}$
$e_6$
$e_5$
Wave as Reduced by Intermediate L.A.

Fig. 5

Theoretically, with an ideal ground wire having zero grounding resistance, there is no excuse for either the station arrester or the intermediate line-type arrester. Actually, however, since the ground wire is some 0.2 microsecond from ground, and the grounding resistance can not always be reduced to the extremely low value required, excessive voltages may reach the machine terminals, and therefore station protection is necessary. Referring to Fig. 5 of this discussion, suppose that a lightning stroke has hit the ground wire. Then a wave starts out on the ground wire, and induces an accompanying wave of the same shape and about a quarter the amplitude on the line wire. Now for a high voltage stroke rising at a fast rate (say 10,000 kv per $\mu$sec), the sparkover voltage of the insulator will be reached before waves of reduction can return from the tower footing, and thus a sparkover is inevitable. At the instant of sparkover the waves on the ground and line wires become equal at a value somewhat lower than the crest of the wave on the ground wire just preceding sparkover. This decrease is due to the reduction of surge impedance. A little later the reflections return from the tower footing and reduce the advancing wave crests on both line and ground wires to a value

$$E = RI$$

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[4] *Interconnection of Primary Lightning Arrester*, A.I.E.E. Trans., March 1932, p. 1234.

where $R$ is the tower footing resistance and $I$ is the tower current. The reduction continues, on account of reflections from adjacent towers, until finally the wave on the ground wire vanishes; but the wave on the line wire moves on and develops a total length equal to the time that it takes the reflections to reduce the voltage at the stricken tower to a negligible value. This may take several microseconds, and in the meantime there impinges on the machine terminal a wave of that length and sustained crest $E = RI$. For example, if $I = 100{,}000$ amperes and $R = 2$ ohms, the incident wave would be 200 kv and would prove destructive unless limited by the capacitor or station arrester. Now there is little hope of keeping $R$ down to such a low value, and so it is seen that either a station arrester with a small capacitor or a capacitor sufficiently large to absorb the voltage slug of length $2T_2$ is a quite necessary part of the protective scheme. Had a perfect ground been instantaneously available at the instant that the lightning struck, no wave could have propagated on the line wire. If the intermediate arrester is between the stroke and the machine, it will greatly reduce the wave on the line wire, and to that extent relieve the station protection.

In the appendix to the paper there are given the equations for the first five entering waves, from which the line terminal and neutral voltages, for either grounded or isolated neutral, can easily be computed. An alternative expression for the $n$th entering wave and for any neutral resistor is given by—

$$V_{ne} = \frac{2E\,(-a)^{n-1}}{Z_1C}\;\frac{(p+G)^{n-1}}{(p+A)^n}\;\epsilon^{-Bt}$$

$$= E\,(-aS)^{n-1}\frac{K}{M}\left\{(\epsilon^{-Bt} - \epsilon^{-At}) + \epsilon^{-At}\sum_{k=1}^{n-1}\left[-\frac{(2t/K)^{n-k}}{\underline{\vert n-k}} + \frac{S^{-k}\,\underline{\vert n-1}}{k\,\underline{\vert n-1-k}}\sum_{r=1}^{k}\frac{(-1)^{k-r}\,(2t/K)^{n-r}}{\underline{\vert k-r}\;\underline{\vert n-r}\;\underline{\vert r-1}}\right]\right\}$$

Where

$$a = \frac{R - Z_2}{R + Z_2} = \text{reflection factor for neutral}$$

$R$ = neutral resistor

$G = (Z_2 - Z_1)/Z_1Z_2C$

Other notation same as in paper.

**Robert Treat:** It is not many years since the orthodox answer to the question "How can I best prevent lightning damage to rotating machinery which is connected directly to overhead lines?" was "By the interposition of a one-to-one transformer between the two." The paper by Messrs. Rudge, Wieseman and Lewis indicates that considerable progress has been made since those days. We no longer feel that an insulating transformer is the best lightning protection; nor do we feel that a transformer constitutes the 100 per cent protection that we used to believe it did.

The problem of protecting rotating machine insulation is more difficult than that of protecting the insulation of transformers and other stationary apparatus because of the lesser margin between normal operating voltage and breakdown strength. Because of this the difficulty of securing a satisfactory degree of protection is somewhat greater than in the case of stationary apparatus; on the other hand, the need for protection is also that much greater.

In an art as old as that of protecting transformers from lightning damage the doctors are not yet entirely unanimous as to the exact place in the picture to be assigned to the lightning arrester. In an art as new as the one covered in the present paper, it is not to be expected that the final word will have been said for some time to come.

It is the writer's firm conviction that an intelligent application of the protective means suggested in this paper will generally reduce the probability of machine failure by an amount sufficient to entitle the protective equipment to be regarded as very cheap insurance. At the same time, considering the newness of the art and the probability of further progress being made in the next few years, it should not reasonably be expected that 100 per cent protection can now be provided under all conditions. One should not be too disappointed, therefore, if he still experiences an occasional failure after the installation of protective equipment; particularly if the protected apparatus has been operating for a period without protection and possibly has already suffered some incipient damage.

**J. F. Calvert:** There are several approximate circuits for the generator winding, each of which has its limitations as well as its applications in surge studies. Messrs. Rudge, Wieseman and Lewis have made use of the assumption put forward by Mr. Boehne, that the armature winding may be treated as a transmission line or cable, but one which permits a very low velocity surge to propagate along it. This scheme will give moderately accurate data on the voltages at the ends of the windings and, in the case of the delta-connected machine, at the midpoint of a phase as well. It is not at all accurate for other points in the winding. It seems to give a reasonably accurate means of calculating the natural period of the machine, though a large number of machines must be tested and calculated to prove this, so that the effect of slot shape and number of conductors per slot could be allowed to enter. It gives a value of voltage between turns at the line end which is too high because of the voltage induced in the adjacent turns by magnetic and electrostatic coupling.

Accurate data on surge penetration into armature windings must as yet depend largely on test data rather than on theoretical analysis. It is unfortunate that no test points have been shown with the test curves of this paper. The writer believes the authors should state for each curve how many machines were tested and what was the maximum variation of test data from the curve. Further, were these all multi-turn coil machines? Did they have similar slot proportions? How many turns per coil were there in the various cases? Was the rotor in or out of the stator?

It is believed that the assumption made by the authors concerning the protective method will result in optimistic rather than pessimistic results for the volts to ground in the machine. The scheme of charging the condenser through the surge impedance of the line is a compromise, for the use of a more lumped impedance with capacity and arresters at the terminals of the machine admittedly will give more complete protection.

It is noted that the authors have assumed a 0/40 wave on the machine side of the arrester, which is located 2,000 ft from the machine terminals. From published performance of arresters, it can be shown that in order to produce such a resultant arrester wave, a 0/18 wave would have to originate on the line. While it is probable that a large percentage of the lightning surges experienced at a particular location will not appreciably be longer than this, longer waves have been measured and may be experienced.

It is felt that a $O$ front flat-topped wave should be assumed as that which passes the arrester, because this is practically what passes an arrester when a severe surge originates on the line.

**E. M. Hunter:** In protecting rotating machines from damage by lightning voltages, consideration must be given not only to the crest but also the front of the voltage wave entering the machine winding so that the resulting voltage distribution in the winding will not damage the turn or neutral insulations. The lightning protection given transformers usually is inadequate for rotating machines because, as Messrs. Rudge, Wieseman and

Lewis have shown, the impulse strength of the insulation of rotating machines is relatively low compared with the impulse strength of the insulation of transformer, lines, etc., to which machines are connected and hence special protective equipment is necessary for this apparatus.

Suitably located special lightning arresters alone at or near the terminals of a machine do not give adequate protection because an arrester limits only the magnitude of the surge voltage to ground and exerts little or no influence on the front of the wave and hence it is necessary to supplement the protection obtained from the special arresters by equipment which will reduce the voltages appearing across the winding turns and at the neutral to values safe for the machine insulation.

In the protective schemes described by the authors, this supplementary protection is obtained by shunt capacitors to ground at the machine terminals. Inductance, located in series between the machine and transmission line also will slope off the front of the incoming voltage wave and a brief summary of what can be accomplished with inductance is given here.

Based on the single conductor theory of traveling waves, the equation of the voltage wave entering a machine caused by a 0-40 μsec voltage wave reaching the machine from over a transmission line through a series inductance is

$$e = \frac{2EZ_2}{Z_1 + Z_2 - 0.0173 \times 10^6 L}\left\{ \epsilon^{-0.0173 \times 10^6 t} - \epsilon^{-\frac{(Z_1 + Z_2)t}{L}} \right\} \qquad (1)$$

where

$Z_1$ = surge impedance of transmission line
$Z_2$ = surge impedance of machine
$E$ = crest of incoming voltage wave
$L$ = series inductance

which shows that with a 0/40 voltage wave arriving at the machine terminals, a voltage wave with a sloping front enters the machine.

The voltage appearing across the machine turn insulation and the reflected voltages at the neutral are dependent upon the slope of the incoming wave. The equation of the slope is obtained by differentiating equation (1), and from the slope, the voltage ($E_T$) across the turn insulation is

$$E_T = \frac{2EZ_2 t}{L} \qquad (2)$$

Mr. E. W. Boehne has shown that the average velocity of propagation of electric waves in machine windings[5] is approximately 10,500 miles per sec. Thus the time required for a wave to travel one turn of a coil is

$$t = 1.5\, D\, 10^{-9} \text{ sec}$$

where

$D$ = $(1.8\, d + 0.1\, mlt)$ = length of turn
$d$ = stacking length of armature core
$mlt$ = mean length of turn of coil

From equation (2) then, the formula for the series inductance to slope the incoming voltage wave is

$$L = \frac{3EZ_2 D\, 10^6}{E_T} \text{ henrys} \qquad (3)$$

where

$D$ = length of turn in inches
$E$ = crest of incoming wave in kilovolt
$E_T$ = maximum allowable voltage across turn insulation in volts
$Z_2$ = surge impedance of machine in ohms

Fig. 6D of the paper shows that a 0.5-μf capacitor at the terminals of a machine, in conjunction with suitable arresters, will prevent the neutral reflected voltages from rising to dangerous values. With the aid of equation (1), it can be shown that a 0.1 henry series inductance at the terminals of the machine will accomplish the same result. However, it would not be practical to use an inductance of this size as it would interfere with the normal transfer of power from a machine.

The authors have also stated that a 0.1-μf shunt capacitor at the terminals of the machine together with suitable arresters will slope off the front of the incoming voltage wave sufficiently so that the resulting voltage distribution in the machine winding will not damage the turn insulation. It can be shown by equation (3) that with the same arrangement of arresters as proposed by the authors, a 0.02 henry series inductance at the terminals of the machine should give the same turn protection for a machine with a surge impedance of 800 ohms. This is considerably more inductance than usually is found in current limiting reactors, induction voltage regulators, etc. However, this value of inductance is conservative, especially for machines with a low surge impedance, and hence a lower value of inductance may often give sufficient turn protection. When there is apparatus having inherent inductance in series between a machine and the transmission line, its protection value should be considered in selecting lightning protective equipment for the machine.

For machines directly connected to overhead lines, the protective schemes proposed by the authors depend upon a definite voltage level being established in an adjacent region of approximately 2,000 ft on all lines out of a station. It is necessary that this 2,000-ft section be free from direct strokes so that the terminal condenser will be charged through the surge impedance represented in this 2,000-ft section.

It has been suggested[6] that this surge impedance could be replaced by a series inductance at the terminals of the machine. This inductance with the capacity at the machine terminals results in an oscillating circuit and to limit the crest of the voltage wave entering the machine to a safe value it would be necessary to install a lightning arrester on each end of the series inductance.

No mention has been made of the size of the inductance required for this purpose. With the authors protective scheme, a 0.5-μf condenser is sufficient to prevent the reflected voltages at the machine neutral from rising to dangerous values. A series inductance together with the terminal condenser should have approximately 5 times the inductance inherent in a 5 per cent load limiting reactor to provide the same protection. An inductance of this size is impractical. Of course, increased capacity at the machine terminals decreases the size of the inductance required.

For protecting the turn insulation in a machine, the inherent inductance in load limiting reactors together with a small capacitance to ground (approximately 0.1 μf) at the machine terminals usually will be suitable provided that lightning arresters are located at each end of the load limiting reactor. This arrangement should prove desirable for protecting grounded neutral machines.

However, in general, the arrangement using series inductance requires much larger capacitors than the schemes proposed in the paper if the series inductance is to be limited to a reasonable value and hence, the authors schemes should prove to be the most desirable for most installations.

**K. K. Palueff:** By taking the transient voltage characteristics of generators given in the paper by Messrs. Wieseman, Rudge and Lewis and the formula presented by Mr. Hagenguth and the writer a year ago[7] for calculation of transmission of lightning through transformers to rotating machines we were able to get quite a definite idea of the magnitude and shape of lightning voltages that can reach generators connected to transmission systems through transformers.

As shown in the paper referred to, lightning voltages reach generators through transformers by means of electrostatic and electromagnetic induction. The energy associated with electrostatic transmission is so small that the capacitance of the low voltage busses, cables, and other parts of low voltage circuit may reduce the amplitude of voltage very appreciably.

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[5] Bibliography 2 of paper.

[6] Bibliography 1 of paper.

[7] *Effect of Transient Voltages on Power Transformer Design—IV*, A.I.E.E. TRANS., Sept. 1932, p. 601.

The bulk of the lightning energy is transmitted by electromagnetic induction, and while its amplitude and shape are affected by the constants of the low voltage circuits, it still is able to produce very high voltages of steep fronts.

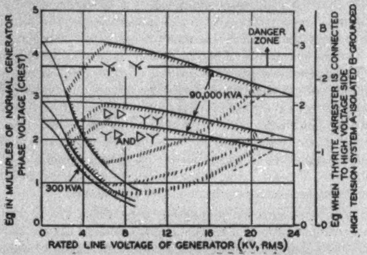


Fig. 6—Lightning Voltage from Generator Terminal to Ground (*Eg*) (Transmitted Through Transformer)

Transformer turn ratio 1:1. Generator surge impedance 600 ohms

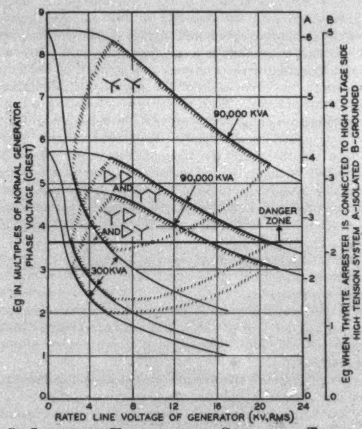


Fig. 7—Lightning Voltage from Generator Terminal to Ground (*Eg*) (Transmitted Through Transformer)

Transformer ratio 4:1 or higher. Generator surge impedance 600 ohms

Voltage transmitted electrostatically may radically be modified by mere change of distribution of the transformer windings on a core. Therefore, no definite idea can be given of the magnitudes of these voltages without referring definitely to a specific type and size of transformer. The electromagnetic induction, however, depends only on turn ratio and the short-circuit reactance of transformers and is absolutely independent of construction features of the transformer. For this reason it is possible to calculate the voltage for practically the entire range of the transformer ratings using for short-circuit reactances of transformers, values typical to the respective ratings.

*Voltage $E_g$ to Ground* (*Figs. 6 and 7*). If the maximum amplitudes of lightning waves that are likely to strike the high voltage winding of a transformer were independent of the length of the waves, then the longest wave would produce the highest voltage at generator terminals. However, on account of the time lag phenomena, the arcover voltage of line insulation and of coordination gap is considerably lower for long waves than it is for the short ones. Thus, it can not be stated apriori whether short or long waves will produce the highest voltage.

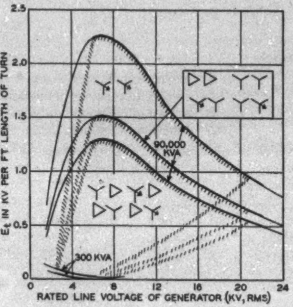
As numerical calculations are quite involved they were confined here to the ½-5 and the 1½-40 waves, and two sets of curves similar to Figs. 6 and 7 were obtained.

It was found that in smaller generators of higher voltage, the 1½-40 wave produces higher voltage to ground that the ½-5, while in larger generators of lower voltages the reverse is true.

Taking in each case the highest of the two voltages, the family of curves of Figs. 6 and 7 were plotted. The amplitudes of waves applied to the high side of transformers were assumed to be limited by a coordination gap and their values therefore were taken to be, for the ½-5 wave 8.55 times the rated phase voltage (crest) of the high voltage winding; and for the 1½-40 wave 5.74 times this value.

Fig. 8—Maximum Rate of Rise *Et* of Lightning Voltage Entering Generator Windings Produced by Impact of ½/5 Wave on High Tension Side of Transformer

Transformer turn ratio 1:1. Generator surge impedance 600 ohms



According to the authors' statement, the allowable impulse voltage from generator terminal to ground is 2.12 times the crest rated line-to-line voltage corresponding to 3.67 times the rated crest line-to-ground voltage. This voltage level is marked in Figs. 6 and 7 with heavy lines as the boundary of the danger zone. The rated line voltage (rms) of the generators is plotted along abscissa while along the ordinate the voltage to ground at a generator terminal is plotted and is expressed in times-normal crest rated line-to-ground voltage of generator. The cross-hatched border encloses the common ratings of generators found in practise. The upper boundary of each area, drawn with a heavy line, corresponds to transformer bank capacity of 90,000 kva. The lower boundary, also drawn with heavy line, corresponds to 300 kva. The left side corner of each area corresponds to 2,300 volts, while the right side corresponds to 22,000 volts. Different cross-hatched areas correspond to different connections of transformer bank. In the transformer connection diagrams indicated on the curves, the high voltage side is on the left. It is assumed that transformation ratio (line-to-line) for Fig. 6 is 1:1, while for Fig. 7 it is equal to or exceeds 4:1. The ratio of high voltage line voltage to low voltage line voltage is the same for all bank connections in the same figure.

The following conclusions can be drawn from these diagrams:

1. 1:1 transformers reduce lightning voltages from generator terminals to ground to safe values in the majority of generators.

The maximum reduction is obtained in Y-delta and delta-Y banks.

2. Lightning voltages on generator terminals increase with increase in ratio of high voltage line voltage to low voltage line voltage until this ratio reaches approximately four. The increase is not proportional to this ratio. The generator voltages are practically independent of it as long as the latter is not materially less than 4.

3. Lightning hazard to ground (major) insulation of generators increases with the kva capacity of transformers connected between high-voltage line and the generator, and with reduction of the rated generator voltage.

4. The surge voltage to ground depends not only on generator characteristics, transformer reactance and turn ratio, but also on the transformer bank connection. The voltage stress in the generator is highest for the Y-Y transformer bank, having both neutrals grounded (or for an auto-transformer) and is lowest for the delta-Y and Y-delta transformers.

5. It appears that without lightning arresters on the high side of transformer, many generators connected to Y-Y, delta-delta, and Y-delta banks having line-to-line ratio approximately 4:1 or greater are in the danger zone.

6. A thyrite lightning arrester on the high voltage side of the transformer eliminates this danger for some of the bank connections, and materially reduces it for others.

*Voltage $E_t$ Across Turn Insulation* (*Figs. 8 and 9*). Voltage between turns depends on the rate of rise of the voltage to ground.

Curves of Figs. 8 and 9 were calculated for the ½-5 μsec wave applied to the high tension side of transformer banks. The 1½-40 wave gives lower voltages.

If mutual inductance between adjacent turns is neglected, then the voltage between turns can be obtained by multiplication of the corresponding value of $E_t$ (of Figs. 8 and 9) by the effective length of the turn (in feet). The effective length of turn is

$$l_{eff} = l_i - \frac{l_a}{18}$$

where $l_i$ is length of turn conductor embedded in slots, $l_a$ is length of conductor outside of slots, 18 is an approximate propagation-constant, which is equal to the ratio of velocity of light to the velocity of propagation of a traveling wave along the conductor embedded into a slot.

If the voltage so obtained is not more than, say 0.66 $E_g$ given in Figs. 6 and 7, then it represents the correct turn voltage. If, on the other hand, this voltage is much in excess of 0.66 $E_g$ it represents voltage in excess of the correct value. In most of the cases it will be found that turn voltage is less than 0.66 $E_g$. The presence of mutual inductance tends to reduce the voltage between turns.

If the value of the kilovolts per foot given in Figs. 8 and 9 is multiplied by 55.4, kilovolts per microsecond are obtained. Different curves correspond to generators of different capacity marked on the curves. It is seen that the turn stress is the highest for the transformer banks of low voltage and high kva ratings and is lowest for banks of high voltage and low kva ratings. Since the strength of turn insulation depends on many factors, it is impossible to draw a danger zone in these diagrams.

It may be added that voltages transmitted through a transformer electrostatically are apt to be much steeper than those transmitted electromagnetically, and therefore are particularly dangerous to turn insulation of generators connected to transformers by means of busses of negligible electrostatic capacitance.

### General Conclusions

With transformer banks guarded only by the coordination gap, the ground insulation of the majority of rotating machines is in danger where they are connected to the transmission systems through transformers with relatively high transformation ratio. A lightning arrester on the high side capable of reducing the incoming lightning voltage to some 70 per cent of the coordination gap level would remove this danger to the generator ground-insulation in most cases, with the exception of the Y-Y grounded neutral transformer (or auto-transformer) banks. In the latter case lightning arresters for the grounded system can be used, and if they are capable of reducing voltages to some 56 per cent of the coordination gap level they will protect the ground insulation of many generators.

However, a lightning arrester on the high voltage side of the transformer capable of protecting the ground insulation of the machine will not, in many cases, protect the turn insulation of the machine as it will not sufficiently modify the shape of the front of the wave. Therefore, to protect the turn insulation a proper condenser should be connected from the generator terminal to ground which would slant the front of the wave transmitted to the generator to a sufficient degree. To eliminate the danger of possible resonance between the protective condenser and the inductance of the circuit, in case of switching, or other oscillatory transients, a thyrite arrester should be placed in shunt with the condenser.

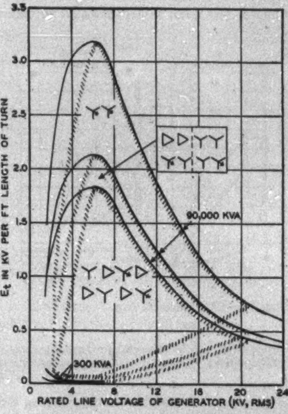


FIG. 9—MAXIMUM RATE OF RISE $E_t$ OF LIGHTNING VOLTAGE ENTERING GENERATOR WINDINGS PRODUCED BY IMPACT OF ½/5 WAVE ON HIGH TENSION SIDE OF TRANSFORMER

Transformer ratio 4:1 or higher. Generator surge impedance 600 ohms

Available formulas permit quite accurate calculation of voltage stresses for any particular installation provided the following data are given:

1. Generator design data. These permit calculation of the surge impedance of the generator and its natural frequency.

2. Arrangement and size of low voltage busses. This permits determination of their effect which is particularly pronounced for voltages electrostatically induced.

3. Transformer kva capacity, turn ratio, bank connection, condition of neutral (grounded or not). This is all that is necessary for the determination of electromagnetically induced voltages. The distribution and dimensions of windings are necessary if electrostatically induced voltages are to be determined.

4. One-line diagram of the substation.

5. The maximum voltage permitted by protective devices (coordination gaps, lightning arresters, etc.) to reach high-voltage terminals of the transformer.

### Impulse Ratio of an Assembled Transformer

The following is a discussion of the paper by Messrs. Montsinger, Lloyd and Clem:

It has been suggested by some that the overall impulse strength of a transformer is proportional to its 60-cycle strength multiplied by the impulse ratio of a barrier of transformer insulation. Such a view is erroneous because it neglects the radical difference in the character and in the distribution of stresses, throughout the complex structure of transformer winding, produced by 60-cycle voltage, from those produced by the impact of an impulse (Fig. 10). This view is no more correct than the claim that the ability of a dirigible to stand a side thrust of a sudden gust of wind can be determined from the uniform steady load test on the dirigible itself and from the ratio of impulse tensile strength to steady load tensile strength of a sample of structural material used for its frame.

If the voltage distribution produced by impulse throughout transformer winding was essentially identical to that produced by 60 cycles, then the impulse strength of a transformer could be judged by its 60-cycle strength. The ratio of the impulse strength to the 60-cycle strength would be the "impulse ratio" of the transformer. This impulse ratio would then be equal to the impulse ratio of the insulating material used and, therefore, could be determined from the impulse ratio test on *samples* of the insulation used. Thus, for example, if impulse ratio of insulation material is assumed to be say 1.85 (this is the ratio of 1½-40 impulse test wave to 3.46 induced voltage test, see Fig. 10A), it could be stated that the transformer as a whole will be able to stand impulse voltage of 1.85 times the maximum 60-cycle voltage that can safely be applied to it. This is so because due to the assumed uniform distribution the impulse voltage between coils, turns, etc., throughout the entire winding would be 1.85 times the safe 60-cycle stress.

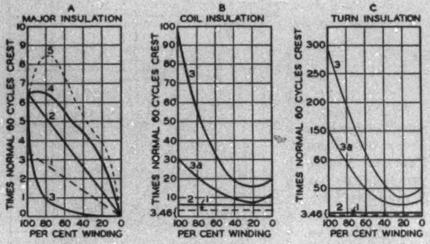


Fig. 10—Comparison of Stresses in a Transformer Produced by Low Frequency and Impulse Tests

Solid lines = impulse test produces non-uniform oscillatory stresses
Dotted lines = 60-cycle test produces uniform steady stresses

Unfortunately, in all transformers with the exception of the non-resonating type, impulse voltage distribution throughout the winding is different essentially from that of 60 cycles. Therefore, when an impulse voltage of 1.85 times 60 cycles is applied to the line terminal, stresses between coils and turns may be 10 or even more times their safe 60-cycle stress (Fig. 10A, B, C). It follows that should their insulation be able to stand only 1.85 times such stress the transformer would fail internally at the application of an impulse wave of 1.85 times 60 cycles. In examining the curves given in Fig. 10 we find that the entire structure except the insulation to ground adjacent to the terminals may be stressed by impulse far in excess of 1.85 times its 60-cycle stress. It is, therefore, impossible to express the impulse strength of a conventional transformer in terms of its 60-cycle strength times the impulse ratio of a sample of insulation. Therefore, two transformers of identical rating and of the same 60-cycle strength, but of a different construction, may have an entirely different impulse strength. For this reason, Fig. 2 of Montsinger, Lloyd and Clem's paper should not be misinterpreted. It illustrates the relation between the impulse strength of a particular insulation barrier and the arcover voltage of a given setting of a rod gap.

The relative values of lightning strengths of the entire insulation structure of a transformer and of a coordination gap, may essentially be different from the one shown in Fig. 3 of the paper, as it depends not only on the strength of the major insulation but also on the strength of coil and turn insulation.

The only conclusions that can be derived from this figure in regard to an assembled transformer is that the margin of safety offered by a coordination rod gap to a transformer is reduced for exceedingly steep waves.

### Detection of Failures Caused by Impulse Test

The transformer subcommittee has made a stride toward the solution of the very difficult problems of commercial impulse testing of transformers. It must be emphasized, however, that the problem is not as yet completely solved. In referring to the detection of dimensionally small damages: extensive damage or a complete failure of major insulation can be detected by methods outlined in the subcommittee's report. However, the puncture of coil or turn insulation, in the majority of cases, cannot be detected by the means recommended by the subcommittee.

It is important to recognize that lightning, both the natural and the artificial, may sometimes produce dimensionally very small damage to apparatus insulation. Such damage in extreme cases may be in the form of pinholes. These punctures often can be detected only with the assistance of a magnifying glass and with a special light, after a transformer is completely disassembled. This may explain why this type of failure is not generally known and even the possibility of its existence sometimes is doubted, although the writer brought this phenomenon to the attention of the Institute as early as 1928 in a discussion[8] which presented arguments in favor of impulse testing of transformers. This type of damage is found in all types of insulation used for transformers and rotating machines.

In this respect, European experience is similar to that of this country. Mr. Norris of Ferranti Ltd., has described[9] the difficulties of detection of local failures in his large 132-kv transformer as follows:

> "After 500 severe surges, there was no external indication that the windings had been damaged by the surge. However, on dismantling the windings and examining them, turn by turn, numerous places of breakdown and partial breakdown were found—all of them between turns and between coils. There was no sign of failure between the high-tension windings and either the low-tension windings or ground."

The writer calls particular attention to the fact that the excitation of a transformer with 60 cycles voltage during the impulse test does not appreciably increase the probability of detection of damages, because the establishment of "follow" power current, under the condition of test outlined in the report is most improbable, particularly in case a failure takes place between turns.

It is possible, therefore, for a transformer unsuitably designed or manufactured to be severely or even mortally wounded during the impulse test in the factory without giving a sufficient indication of the distress to justify its rejection. It may take weeks and even months until one of these local breakdowns will develop into a complete failure under the service stresses.

In view of the above it is hoped that in the near future, a more positive method of determining the condition of transformer insulation after the impulse test will be found. This would place commercial impulse testing on a more firm ground.

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[8] A.I.E.E. Transactions, October 1928, p. 1013.

[9] *Electrical World*, December 27, 1930.

### COMPARISON OF 60-CYCLE INDUCED VOLTAGE TESTS WITH IMPULSE

In transformers of ordinary construction, the impulse and 60-cycle tests differ radically in amplitude, duration, and distribution of stresses produced throughout the winding. In transformers of non-resonating construction, they differ essentially only in the amplitude and duration.

Separate comparison is shown in Fig. 10, of stresses produced, in major insulation (insulation to ground), coil insulation, and turn insulation, by these two tests. It is assumed that the applied wave is 1½-40 with amplitude just below that necessary to arc over a standard test gap. The amplitude of the induced voltage test is assumed to be 3.46 times normal phase voltage (rms). All voltages are expressed in multiples of normal voltage (crest).

*Voltage to Ground—Fig. 10*A.

*60-Cycle Test.* Line 1*A* gives voltage for transformers of all types.

*Impulse Test.* Curve 2 gives voltage distribution in an ideal non-resonating transformer.

Curves 3, 4, and 5 give voltages in ordinary transformers. Curve 3 indicates the initial distribution, 4 and 4 the maximum produced by oscillation subsequent to the impact of the wave. Curve 5 corresponds to ultimate voltage that can be obtained in a transformer with a relatively short natural period, while 4 corresponds to a transformer with longer period.

It is interesting that an appreciable lengthening of the applied wave beyond 40 μsec does not lower its amplitude very much as the impulse ratio or arcover voltage of a rod gap for 1½-40 is only some 10 per cent higher than that of a 1½-100 wave.

However, the lengthening of the applied wave from 40 μsec to 100 μsec increases very appreciably the internal voltages to ground in ordinary transformers (curve 4).

*Voltage Across Coils and Turn Insulation—Fig. 10*B, C.

*60-Cycle Test.* These tests produce voltage stress of 3.46 times normal.

*Impulse Test.* Curve 2 shows voltage stresses in an ideal non-resonating transformer. Curve 3 shows the approximate range of stresses in ordinary transformers of different construction and proportions. Location of a given coil or turn in a winding is indicated by the abscissa.

Duration of stresses produced by 60-cycle test is the same for all elements of insulation structure in all transformers. Duration of stress produced by an impulse wave in an ordinary transformer is very different for different elements and for the same elements in different parts of the structure.

One of the conclusions that can be drawn from the above is that no matter what the ratio of impulse of the two tests, they can not be made equivalent in any transformer with the sole exception of a non-resonating type. In case of a non-resonating transformer, the duration of stress is the same for all elements.

### RELATION BETWEEN LENGTH OF APPLIED WAVE AND VOLTAGE TO GROUND

It has been shown before that the internal voltages, from winding to ground, when expressed in per cent of the amplitude of the applied wave, increase with increasing length of the applied wave, until each point of the winding reaches its possible maximum. This possible maximum is indicated by curve 5, of Fig. 10A.

In case the applied wave has a flat top and a sufficiently steep front (say 2 μsec or less) the maximum is reached when the length of the wave is ½ of the duration of the natural period *T* of the transformer. When the applied wave has an exponential tail the maximum, theoretically speaking, is never reached but some 90 per cent of the maximum is produced by a wave which decreases to half of its crest value in about *T* in 2*T* microseconds.

The above relations between the length of the applied wave and internal voltage to ground hold for the middle third of a transformer winding.

It should be appreciated, of course, that different points along the winding require a different minimum length of the applied wave to cause these points to reach 90 per cent of their possible maximum. It can generally be stated that the shortest wave is required for the third of the winding next to the grounded neutral and the longest for the third next to the line terminal.

From this it would follow that to subject the major insulation of an ordinary transformer to the maximum stress, it is necessary to apply as long a wave as possible. In any event, at least as long as *T*.

This would be true provided the applied waves were all of the same amplitudes. However, this is not the case as the amplitude of test waves is assumed to be fixed by the arcover strength of a rod gap of a given setting. On account of the time lag of such a gap, the amplitudes of very long waves are appreciably smaller than those of very short waves.

Thus an increase in length of the wave on one hand increases the values of internal voltages relative (in per cent) to the amplitude of the applied wave, but on the other hand, reduces the amplitude of the latter, and therefore reduces the absolute values (in volts) of the internal voltages.

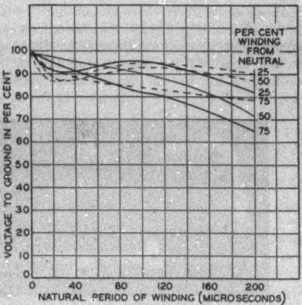

FIG. 11—EFFECT OF THE LENGTH OF THE APPLIED WAVES ON THE VOLTAGES TO GROUND IN WINDINGS OF DIFFERENT NATURAL PERIODS, WHEN THE AMPLITUDES OF THE WAVES ARE CONTROLLED BY A ROD GAP OF THE SAME SETTING

Voltages are given in per cent of the maximum voltages produced by the respective critical waves for 3 points of the winding

Solid lines = 1½ – 40 wave
Dotted lines = 1½ – 100 wave

Numbers on curves indicate the distance of the points from neutral in per cent of total length of winding

The conflict of these two phenomena results in the existence for each transformer of a wave of critical length which produces the maximum absolute stresses within parts of the windings. Waves shorter or longer than the critical produce lower stresses. However, there is quite a wide range of waves on both sides of the critical length that produce voltages within a few per cent of the maximum.

These considerations permit the calculation of the curves shown in Fig. 11. Three curves correspond to 75, 50 and 25 per cent point (measuring from grounded neutral) of a winding, they show the voltages produced in transformers of various natural periods, by a 1½-40 μsec wave (recommended by the subcommittee as standard for impulse test) and by a 1½-100 μsec wave.

The voltages are expressed in per cent of maximum voltage produced at the same points of the winding (of a given natural period indicated by the abscissa) by waves of the respective critical lengths.

The curves indicate that the recommended waves subject the internal major insulation practically to its maximum possible service stress in transformers of natural periods not much longer than say 100 μsec (corresponding to a natural frequency of 10,000 cycles and higher).

In transformers with materially longer natural periods the applied wave must considerably be longer to duplicate the possible internal service stress. It appears therefrom that the 1½-100 wave in contrast with the 1½-40 wave would subject practically all transformers to stresses of essentially the same relative severity, since the natural period of the majority of transformers is less than 200 μsec.

The above analyses were made for transformers with grounded neutral. Essentially the same relation holds for transformers with isolated neutral or connected in delta. The difference in details for the two phenomena is believed to be sufficiently obvious to make further discussion of it here unnecessary.

**F. J. Vogel:**[*] In the formulation of standards or rules for testing, it is necessary that they be sufficiently severe to give reasonable assurance that the apparatus will withstand service conditions, and that the fact that the apparatus has or has not fulfilled the requirements can reasonably be certain of determination. The question of severity in the case of surge testing hinges upon the test gap length, the magnitude of the surge impressed, the polarity of the surge and the shape of the wave. These factors should be chosen with the idea that they would result in transformers of adequate strength for service conditions.

However, some of these factors have been questioned. The proposed test gap insures that there is a margin between the coordinating gap and the apparatus. The magnitude of the test, as determined by the present proposals, in the writer's opinion probably is low for the higher voltage classes, because the proposed rule of 10 per cent above the full wave value of the test gap does not provide a test up to the strength of the major insulation. The polarity of the wave has been questioned. This, however, involves more than just the polarity but also the preceding recommendations, provided obtaining proper insulation of the transformer is the sole thing in mind. It is not believed that this is an essential point in the obtaining of good transformers. The choice of the wave shape is dependent upon two factors. One is the possibility of producing the wave and the other is the question of what represents the worst conditions in service. The steepness of the wave front which may be obtained is limited by the transformer and the surge generator, as has been shown by Mr. Bellaschi (TRANSACTIONS A.I.E.E., December 1932, page 936). Nevertheless, the gap flashover close to the transformer leads to the highest coil stresses and so similar effects to those of the steepest wave fronts can actually be obtained. The length of the wave is dependent upon the inductance of the transformer and the capacity of the surge generator. A long wave can be obtained therefore provided the surge generator capacity is sufficiently great. The criterion for this is the length of the longest surge expected in service. From field data which have so far been collected, there are no indications that lightning surges longer than 40 microseconds to half value will be found in service.

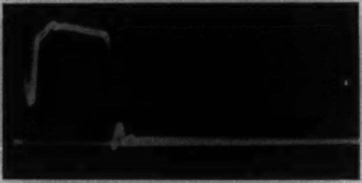

FIG. 12—CATHODE RAY OSCILLOGRAM SHOWING OSCILLOGRAM WITHOUT INDICATION OF INTERNAL TRANSFORMER FAILURE

It is of interest that in the discussion the question of the length of wave is raised. Considerable pains are taken to show that a transformer with a long period does not develop oscillations to the fullest extent with surges of relatively short lengths. This theory was advanced by Mr. J. K. Hodnette in 1929 (TRANSACTIONS A.I.E.E., January 1930, page 68). In the discussion of Mr. Hodnette's paper, some engineers claimed that the maximum full wave lightning voltages were high enough and the period of all transformers short enough so that the grading of insulation was hazardous. Since then, the maximum lightning voltages seem generally to have decreased more nearly to Mr. Hodnette's values. It has also been discovered and agreed to by all engineers that some transformers do have relatively long periods, as Mr. Hodnette claimed. It is apparent therefore that grading of transformer insulation may not be hazardous provided the wave is of the order of 40 to 50 microseconds to half value. No records of natural lightning have been produced so far as the writer knows where the wave is more than 40 to 50 microseconds long to half value. No reason for increasing this value in the Test Code can be seen unless it be to impose an artificial difficulty in the way of certain meritorious designs.

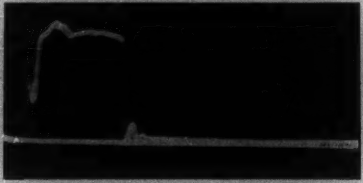

FIG. 13—CATHODE RAY OSCILLOGRAM, INDICATING FAILURE BY THE SLIGHT DEPRESSION IMMEDIATELY AFTER THE CREST OF THE WAVE

Compare this with Fig. 12. This indication is very sensitive of any coil-to-coil damage near the line end of the transformer

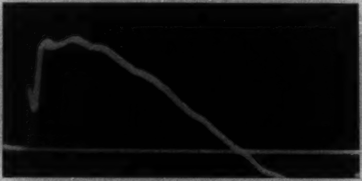

FIG. 14—CATHODE RAY OSCILLOGRAM, SHOWING COMPLETE FAILURE OF THE TRANSFORMER

In this test, a wave as high as that in Fig. 13 was impressed, but the gap did not flash over. Two indications of failure were obtained simultaneously

The question of certainty of detection has been raised by several engineers. It appears that extensive damage or complete failure of major insulation can be detected by the methods outlined in the subcommittee's report. Another believes that puncture of coil-to-coil and turn-to-turn insulation, in the majority of cases, cannot be detected by the means recommended. This does not agree with the writer's experience, and the cause must be that it is not based on the same equipment and methods. If it is caused by difference in design practise, it certainly is a serious matter. It is no less serious if due to lack of experience or technique in testing and observation. It is to be hoped that these difficulties will be removed by further testing experience.

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[*] Discussion on *Progress Report on Impulse Testing of Commercial Transformers.*

The company with which the writer is associated has tested many transformers up to or higher than the surge voltages which are recommended by the Transformer Subcommittee. These have been distribution transformers, core type transformers with small round wire coils, core type transformers with ribbon wound coils, and shell type transformers. Some of these have been given a great number of tests, a thousand or over in the case of some distribution transformers, and when disassembled with the greatest care, no visible signs of deterioration were found. However, a number of transformers have failed, as indicated by the means available. It may be possible to design a transformer between these limits, which requires some responsibility to be assumed by both the manufacturer and the purchaser.

The experience of an English engineer, Mr. Norris, has been cited. It is my opinion that if the transformer described by Mr. Norris had been tested with excitation, or if cathode ray oscillograms and oscillograms of the excitation voltage and current were obtained and other means used as described in the subcommittee's report, indications of the extensive failures described would have been obtained. It is clear on the one hand that such tests were not possible in 1930 and on the other that transformers built in 1930 and possibly incapable of withstanding surges can be replaced in 1933 with transformers capable of withstanding repeated surges.

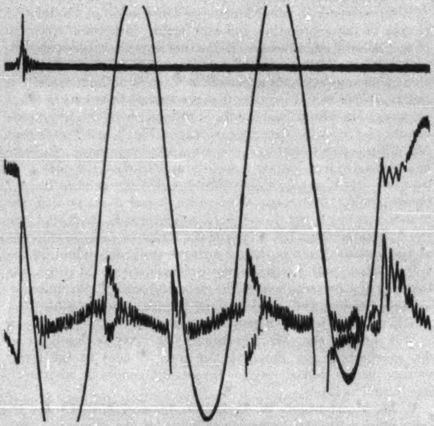

Fig. 15—Oscillogram of Excitation Voltage and Current During a Transformer Failure

The top line is an indicator only to show the instant that the surge occurred. The middle wave shows the current flow, which flowed for 2½ cycles after the surge occurred. The lower-line shows the disturbance to the voltage wave. Power follow is rarely continuous, but does do further damage, even when it occurs locally, and for a part of a cycle only

The writer cannot agree that excitation does not increase the probability of detection of failure. In the case of a single failure between turns, with no further testing, it could not be said to be a definite indicator. But in actual practise, such a failure soon involves other turns and enhances the probability of power flow, even for a fraction of a cycle. In a station, lightning struck a tower close by, and one of the transformers failed. The failure involved one coil only. No damage was found elsewhere. If power had not been available, it is felt that nothing would have happened. The bank was delta-connected and only one transformer showed evidence of failure, although two were subjected to the same surge voltages. In the other one, due to the phase position, power did not follow. This clearly shows the value of power-follow testing. We have found that in failures of some transformers some indicators are more sensitive than others, and that power-follow is a very essential indicator. We have taken oscillograms of the low voltage current in most transformer tests, to show the time of the surge, and to show any power flow taking place. Examples of oscillograms taken during transformer tests are shown in Figs. 12 to 15.

The statement has been made that surge tests are more sensitive, if anything, than the present 60-cycle or induced tests. This is believed to be true.

Another engineer has cited the case of three transformers, *A*, *B* and *C*, where *A* fails through the major insulation but where *B* and *C* apparently pass the test. *B* further is assumed to be damaged but *C* to be good. If this can be the case, it is stated that the test without a detector is worse than useless. This statement would not universally be agreed to even without as sensitive a detector as we now have. A potentially dangerous piece of equipment was detected (transformer *A*). Transformer *B* would be in no worse shape then after the first line surge had struck it, and at worst but a small proportion of its possible life has been taken away. Actually, however, there will be few transformer *B*'s. Nevertheless, there is a suggestion here. Possibly the correct surge test would consist of repeated tests, which would increase the incipient damage done until actual failure by power follow or other indication, to make it more comparable in length to the 60-cycle tests.

**F. J. Vogel and V. M. Montsinger:** The subcommittee was very glad to get so many discussions of the report. As may be inferred from the title, the report merely marks progress. We realize that it will, no doubt, be necessary as time goes on to make changes and modify it as we gain further experience.

Most of the points mentioned by the discussors have been considered by the subcommittee. However, this does not mean that these suggestions will not be given further consideration. One or two points in particular may be mentioned. Mr. Sporn suggests that negative waves instead of positive waves be used since in practise the highest lightning voltages are of negative polarity. The best argument for using negative waves is not the one mentioned but that the negative wave flashovers of most insulators and coordination gaps are higher than positive wave flashovers. However, unless the stresses imposed in windings by a negative wave are more severe than those imposed by a positive wave (of the same voltage amplitude) the question of polarity of waves merely is one of severity of test or of what level of impulse voltage should be used in making the impulse tests. So far as we know there is no difference in the stresses imposed by either wave of the same amplitude. Therefore, what Mr. Sporn really suggests is that the impulse level for testing be raised.

When establishing the level of the test gaps the committee felt that these gaps imposed as severe a test as was justified at the present time. We have no assurance, it is true, that the tests proposed are of adequate severity. If further experience indicates that it is desirable and necessary to raise the impulse level, manufacturers will be very glad to do so.

As to the suggestion that volts instead of gap spacings be used, the subcommittee as stated heretofore has given this very careful consideration. The committee recommended the method which it was felt would come nearest giving the same results when used by the various laboratories.

When the different laboratories can check each other in kilovolt values the subcommittee again will consider changing over to volts. Actually, we do not see why the use of the gap as a measure of impulse tests should be objected to as it fulfills its intended purpose very well indeed.

The other points raised, including the question of detection of damage, etc., will be referred back to the subcommittee for further consideration.

In conclusion, the subcommittee appreciates very much the suggestions offered. It is felt that it is progressing along the right lines, and that the present proposals should be given one or two years trial before attempting to make any material changes.

**F. J. Vogel:*** Mr. Brand has brought up the point that due to the relations of transformer insulation and the coordinating gaps at the very short time lags, the impression may be obtained that the whole scheme of insulation coordination using gaps is of little value. Mr. Brand has given important reasons why this impression is not justified. The original intent of the coordination work was to provide coordination for traveling waves, and not direct strokes, as may be recalled from the original recommendation of reduced line insulation for one-half mile from the transformer. As Mr. Brand has stated, extremely steep fronted surges are not to be anticipated, because of distortion from corona loss, and also because of the lumped capacitance of the station and transformer. These views are confirmed by the remarks of Messrs. Fortescue, Peek, Putman and others. It is essential therefore to protect stations from direct strokes by ground wires, in which case the present coordinating gaps will serve as real protection to the transformers and equipment if properly installed.

Mr. Sporn has raised three points, which are discussed as follows:

*1. Strength Against Negative Waves.* To the best of the writer's knowledge, no data for the strength of transformer insulation against negative waves are or have been published. There are no data in the paper by Messrs. Montsinger, Lloyd and Clem for the strength of transformer insulation against negative waves. The statement is made in their paper that "polarity also affects the flashover, the negative wave *usually* requiring the higher voltage." No question of this statement is raised, as it is true usually, but exceptions do arise. Mr. Sporn does not feel that it is shown conclusively that the strength of transformer insulation is approximately the same for positive and negative waves. It always is a question as to the amount of data required to be conclusive. For the purpose of the paper, I believed the data provided to be sufficient, but it is proved further by tests I have made on transformers and other data not easily presented.

However, reference to Fig. 9 of the paper will show that the negative points preponderate above the line and the positive below, and there is reason to believe that there is a slight difference, possibly as much as 5 per cent in favor of the negative wave. Considering the variations in individual readings, it was not felt desirable to claim such a difference, and it was necessary to state that the results for negative and positive waves were only approximately the same.

*2. Present 60-Cycle Tests.* The surge strength of transformer major insulation and of the coordinating gaps has been determined in the laboratory, both by tests on insulation samples and in specific instances by tests on transformers. Mr. Sporn's unsatisfactory experience can be explained in several ways. The paper specifically limits itself to *major* insulation, and it is possible that the windings of his transformers were relatively weak. Lightning arresters of various manufacture and age are not uniform in performance, and in all cases must be installed properly to be effective. Coordinating gaps must also be installed with due regard to location and grounding. Further than this, it has been shown possible with extremely short waves to cause simultaneous gap and bushing flashovers, and it requires no stretch of the imagination to explain a failure of the coordination system by a direct stroke of lightning.

*3. Lightning Arrester Recommendations.* In former years laboratory data to show that lightning arresters were effective were not available. It is now a simple laboratory experiment to surge test a transformer and an arrester in parallel with the coordinating gap, and show the relationships which are claimed. Whether an arrester is justified economically may be questioned in some instances, but that it will perform the function of preventing flashover of the coordinating gap in a transformer installation can readily be demonstrated.

Several have brought out the point that windings may not be insulated up to the level of the major insulation as determined by the 60-cycle standard disruptive tests. I had believed that I had placed special emphasis on this point. Nevertheless, the reemphasis placed upon this point by Mr. Montsinger and Mr. Palueff cannot help but be beneficial. However, I would like to bring out the fact that the impulse ratios of all insulations, even under oil, are not the same, and that under no circumstances can the fact that a transformer has withstood the standard overpotential and induced tests be used as evidence of its surge strength. It is not always economical or desirable to design transformers with even approximately uniform surge voltage distributions, and this constitutes another reason for making surge tests on transformers.

With reference to Mr. Montsinger's discussion of the relative shapes of the coordiating gap and major insulation time lag curves below 2 microseconds, it does not appear that his generalization is safe. I have tested transformers and models at very short time lags against the coordinating gaps without insulation failure, which would indicate that the shape of the curves is not always as Mr. Montsinger shows. I believe, therefore, from these results and from the data on my curves, Fig. 3 and Fig. 5, that Mr. Montsinger's tests and my own were not made on comparable structures. Also, it is to be noted that the time of 2 microseconds is not definitely stated, but it is stated as *about* 2 microseconds. Reference to my Figs. 3 and 5 shows that the curves are flat down to about 2 microseconds, and that the closest relationships (allowing for the factor of safety) will exist at times somewhat less than 2 microseconds, depending on the voltage class, and also upon the construction used. Care was taken in the presentation of the data and analysis to make allowance for some variations, and not to make an exact statement which could not be shown generally to be true.

It is pleasing that Mr. Montsinger has come as closely as he did in checking my proposals for test voltages in the lower voltage classes, considering the present differences in laboratory results and methods.

**V. M. Montsinger, W. L. Lloyd, Jr. and J. E. Clem:** In connection with Mr. Putman's criticism of the statement that the gap is considered as a device for setting a maximum to the voltage which may be applied to the station apparatus, we can not see why this statement is criticised because even though the gap does chop the wave it certainly limits the incoming voltage to a lower level than if it were not present. The word "limit" does not necessarily mean that it maintains the voltage at a constant kilovolt value regardless of wave shape.

In his remarks about the coordination gap not being a protective device, Mr. Putman indicates that he has missed the point entirely, while Messrs. Sels and Beck agree with the authors. The requirements of ideal protective equipment needed can be formulated without reference to transformers. They are: (1) goes into operation at a voltage in excess of the operating voltage; (2) maintains a liberal margin below the strength of the apparatus; (3) does not cause any additional voltage strains, either of magnitude or gradient; (4) does not cause a system outage; and (5) is not damaged itself. The plain gap has been tried and found wanting in some of these respects. The coordination gap serves as a basis of design and test at the factory and in the field as a measure of the minimum protection required. The choice of the protective equipment must rest with the purchaser who is responsible for the safe and successful operation of the apparatus.

Mr. Putman criticises our wording on protection offered by sphere gaps. What the paper really says is that by using the

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*Closing discussion on *Factors Influencing the Insulation Coordination of Transformers.*

sphere gap a more nearly constant factor of safety is maintained throughout the range of waves than if only a rod gap is used. We do not believe that Mr. Putman can question this statement.

In connection with the suggestion that it would be better to locate the coordination gap some distance away from the transformer we believe that two gaps are preferable, the one further away being set slightly higher than the one near the transformers. Taking everything into consideration it is quite desirable to have at least one gap as near the transformer as possible.

Mr. Sels suggests the use of sphere gaps for impulse testing of transformers on the basis that the time lag curve of the sphere gap is more nearly the same as that of the transformer interior than is the time lag curve of the coordination rod gap. This is a good argument and one which cannot lightly be cast aside. However, since the time lag curve of line and bus insulators is more nearly the same as that of the rod gap, it seems better to use a rod gap for the measurement of the test voltage. However, should a design of coordination gap be worked out using a sphere gap in parallel with a rod gap then it would be quite logical to make the impulse test with such a gap.

We agree with Mr. Sels that the coordinating gap has one undesirable feature; namely, it produces tripouts, and to avoid this we recommend the use of lightning arresters which are intended to prevent the gap flashing over.

We feel quite sure that Mr. Sporn's ideas and ours in regard to the establishment of a uniform level of station insulation are identical. The major parts of the station insulation consist of the bus supports, disconnecting switch insulators and apparatus bushings. A bus short-circuit can be just as disastrous when it is initiated by the flashover of an apparatus bushing as it is when caused by flashover of the bus insulator itself. Therefore, nothing is gained by increasing the flashover of the bus insulation if flashover of apparatus bushings can cause a bus short-circuit. However, if the apparatus bushings can flash over without causing a bus short-circuit, it is obvious that short-circuit can be prevented by increasing the bus insulation. No doubt this is the situation which Mr. Sporn has in mind.

In answer to Mr. Sporn's question (3): briefly, a cable will be a protective device when its capacitance is such that it can reduce the crest of the surge and its front to values that are harmless to the connected apparatus. This question has been fully discussed in a paper entitled *Traveling Wave Voltages and Cables* by Brinton, Buller and Rudge and the discussion by Clem published in the TRANSACTIONS, March 1933 on pages 121 and 129.

Mr. Sporn again raises the question as to why coordination is not as yet made exclusively on the basis of volts. Of course, this is the logical course and is the goal toward which we are all working. At present, however, it is quite clear that the rod gap is the best means of getting along. The reasons for this have been given in the paper.

Mr. Vogel cites the case where the impulse ratio of varnished cambric is somewhat lower than that of pressboard and oil in series, which was used in his replica of major insulation and in the insulation barrier cited in our paper. While it is true that the impulse ratio is not always the same for various materials the insulations used in our transformers for major insulation are generally herkolite cylinders and herkolite flanged collars or pressboard employed on the outside of the windings for shields, etc. These materials have approximately the same impulse ratio. We do not depend on varnish cambric for major insulation.

In connection with determining the time lag of the sphere gap shown in Fig. 2 the voltage values shown obviously were not taken by a sphere gap but were determined by the divider deflection. The divider resistance ratio was not used but the ratio was determined by independent sphere gap calibration, It is true that in making these measurements a great deal of care was necessary to overcome errors due to corona so that the special divider had a very high degree of fidelity.

As stated in the discussion of Mr. Vogel's paper the impulse value of 2.35 was obtained on other insulation and winding set-ups long before the tests were made on the particular barrier as cited in the paper.

It does not seem that Mr. Vogel is very consistent in advocating that the lowest values should be given the most weight when he found an impulse ratio of 1.63 for the varnished cambric, and at the same time gives an impulse ratio of 2.2. Mr. Vogel does not make himself very clear where he states that "for shorter and shorter time lags the impulse ratios of all elements approach infinity, and infinity over infinity is rather an indefinite indeterminate ratio to use to determine the factor of safety." The impulse ratio as generally understood for solid insulation is the ratio of the impulse breakdown divided by the 60-cycle one-minute breakdown kilovolt. We agree with Mr. Vogel's suggestion and our paper states that the ground wire protection should be provided over stations as a protection from direct strokes. However, there are some fairly high voltage outlying stations where the expense required to provide either lightning arresters or overhead ground wire protection cannot be justified. Our suggestion is that for these cases the next best thing is to provide a combination coordination gap which has volt-time characteristics similar to transformer insulation, thereby maintaining a more constant factor of safety regardless of the lightning wave shape.

We also agree with Mr. Vogel's suggestion that the combination protective device gap should be protected by a lightning arrester. This device then not only protects the transformer but protects service from outages. He points out, that in Table IV the ordinary sphere gap is impractical due to its size. For 220-kv circuits it may be impractical to use one meter spheres but for circuits of 138.5 kv and below the sizes of spheres required do not appear to be impractical at all. However, it is practicable to get sphere gap protection for any voltage by using several small spheres in series as mentioned in the paper and as outlined in Mr. Palueff's discussion.

In connection with Mr. Vogel's criticism of Table V we would again like to emphasize the point that we can make no definite claims for any protective device under the most severe direct stroke but that the use of the sphere in combination with a rod gap certainly will tend to maintain a more constant factor of safety and it is this feature which makes the sphere gap look promising.

The terms "outdoor" and "indoor" *versus* "exposed" and "unexposed" have their advantages and disadvantages. We considered that the terms outdoor and indoor were preferable, but we are open to suggestions for better terminology.

The value of 4 in. given in Table I for 13,200 volts is incorrect. It should be 4¼ in. on the basis that 13,200-volt equipment is in the 15,000-volt class.

With reference to Fig. 4, curve *D* represents the equivalent rod gap of our present power transformer bushings. Curve *C* is proposed as a standard level. If power transformer bushings can be brought down to level *C* without considerably decreasing the 60-cycle wet flashover values by means of a gap, it may be found possible in the future to line up all transformers with curve *C*. Mr. Vogel apparently objects to gaps on bushings for two or three reasons, none of which we believe are really good reasons. We would call Mr. Vogel's attention to the fact that it is now and has been standard practise for several years for some of the European manufacturers to gap all of their bushings, these gaps being provided primarily as a protection to the porcelain in case of power arcs. If the impulse flashover of bushings is to be standardized, and there does not seem to be any question but that they should be, the use of gaps will become an absolute necessity to take care of length variations in bushings of different manufacturers. They should be welcomed by both manufacturers and operators.

We agree with Mr. Beck's suggestion that the use of a lightning arrester in combination with a coordination gap is very desirable because it flattens out the wave and acts more nearly like a sphere gap in this respect. This is true particularly of modern thyrite arresters. However, we do not believe that the manufacturer of either autovalves or thyrite arresters will claim that even a modern arrester can always handle the most severe direct strokes. It is for this reason that it is suggested that the sphere gap might be used to advantage where ground wire and direct stroke protection is not practical. While the paper states that the best sphere gap protection can be provided with covered spheres yet it is not absolutely necessary in all cases that the spheres be covered to give considerable added protection. As pointed out in the paper the low frequency flashover can be held under rain conditions to with 3½ to 4 times normal voltage with uncovered spheres. Under dry conditions this corresponds to about 8 times normal voltage. It is shown that even with this setting considerable protection is offered for really steep front waves. Mr. Beck suggests the use of the gaps patented by Allcutt some years ago. Our paper points out the possibilities of using two or more gaps in series shunted by capacitance and resistance. While these special combination gaps may be used, our tests indicate that in view of the very close agreement in the volt-time characteristics of the sphere gap and insulation from the standpoint of maintaining a constant factor of safety there is no gap better than the sphere gap for this purpose.

Mr. Fielder questions the accuracy of the humidity correction curves as determined from the data points given in Figs. 7 and 9. The actual slope of the curves was determined not with the few points listed, but with a very large number of points taken under slightly different conditions. Therefore, the slope of the curves was fairly accurately determined. A large amount of data for negative polarity has been obtained and nothing to date indicates that the humidity correction for negative polarity is different from the corrections for positive polarity. The same corrections have been used for both. Should additional data indicate the desirability for modifying the values proposed we will, of course, make the necessary changes.

We have believed in the past and still have every reason to believe that the sphere gap is sufficiently accurate for impulse voltage measurements when the crest voltage of the test waves that are in use at the present time are being measured. The time-lag of the sphere gap as indicated in Fig. 2 was obtained by applying overvoltage to the spheres: they were arcing on the rising front of the wave which reached a crest value in 1.5 $\mu$sec. The curve was obtained by comparing the oscillogram deflections of the sphere arcing on the front of the wave with deflections obtained with the spheres arcing on the crest of the wave. Voltage as measured by the oscillograph is considered accurate when it is referred to sphere breakdowns on the crest of the waves at approximately the same voltage. It is felt, however, that the ohmic ratio of the oscillograph voltage divider can not be used by itself to obtain kilovolt values since the effective ratio changes throughout the wide range of test voltages; and changes with the wave shape.

Mr. Monteith points out that data obtained from the United States Weather Bureau indicates that humidities as high as 9½ grains per cubic foot have been recorded. This fact is not questioned. We do not feel that it is either necessary or economically advisable to increase the insulation and accordingly the cost of apparatus to take care of these few exceptional cases. If the industry desires this extra insulation the manufacturer certainly will have no objection.

Mr. Monteith's curves showing glaring inconsistencies in equivalent gap spacings, emphasize a point which is somewhat outside the scope of this paper and that is—laboratory practise and technique should be standardized. If the different laboratories can not agree any closer on these equivalent gaps than indicated by Mr. Monteith it is no wonder that they do not agree on kilovolt values. The trouble apparently is not with the gaps but with the methods of making the tests. These large differences emphasize the need of some simple method of defining insulation levels. There is nothing more simple than an air gap.

Mr. Monteith's suggestion of the use of kilovolt values plus a correction factor for humidity is of course contingent on the ability of the laboratories being able to get the same kilovolt for the same test piece.

The authors of this paper are rather surprised to note that the burden of defending the action of the Transformer Sub-Committee recommending the use of the point gap for coordination purposes has fallen on them. In view of the discussions presented, the authors feel it desirable to express their views which are as follows:

1. The logical basis of expressing the impulse strength is in kilovolts.
2. The method standardized by the Institute for measuring voltages is the sphere gap.
3. Since one large manufacturer (see discussion by Fielder) does not use the sphere gap, difference in the value of kilovolt given for the flashover of this same test piece has resulted.
4. In spite of this difficulty it is necessary that the industry carry on.
5. The use of the point gap with the flashover value expressed in inches rather than in kilovolt offered an expedient for establishing the design and test level of transformers to tide us over until such time as kilovolts could be used.
6. The use of the point gap with the flashover value expressed in inches minimizes the effect of slight differences in wave shape, and the effects of atmospheric conditions.
7. It is believed that impulse testing of transformers should be based on the rod gap until the technique of the different laboratories can be standardized to the point where the same kilovolt for the same test piece will be given by all laboratories for the 0.5/5 wave as well as for the 1.5/40 wave.

**C. F. Harding and C. S. Sprague:** Within the last few years much progress has been made in the field of surge protection of the lower voltage distribution transformers, both in the modification of the design, and in the methods of protection employed in service. Except for statistical records kept by a few of the larger operating companies, this phase of lightning protection was more or less neglected until comparatively recently. However, the results of the researches of the last few years, and the cooperation of the transformer manufacturers in modifying the designs for improved surge-resisting characteristics, indicate that a practically surge-proof distribution transformer is now an accomplished fact.

It is gratifying to note, in the discussion by Mr. D. W. Roper, that the interconnection of the secondary neutral and lightning arrester ground, which was strongly recommended in several papers, including those of the authors of this paper, at the winter convention of January 1932, has been showing up so well in the cases where this "interconnection" was made.

Referring to Mr. Hodnette's limitations of the favorable use of the interconnection of the secondary neutral to the primary lightning arrester ground, it should be noted that the necessity of multiple low resistance secondary grounds was emphasized in our paper. His general limitation of such an interconnection in cases making use of delta-connected power secondaries may be unnecessarily rigorous, however, since such secondaries with the mid-point of one phase grounded, in accordance with Chicago practise, represented one of the most favorable protective applications of the interconnections tested. The use of secondary arresters is recommended to avoid excessively unbalanced potentials in this case. Considerable protection is provided by the interconnection, however, without these arresters.

The discussion by Mr. Opsahl would represent a correct interpretation of the two oscillograms presented in the paper if a failure of insulation to ground were under consideration but the type of failure of insulation reported in our paper, *i.e.*, "primary winding . . . broken down between turns or layers" was not only apparent from the comparison of Figs. 5 and 9 of our paper but more forcefully evidenced in the many other oscillograms of these same tests not available for the paper, several of which are reproduced in *Bulletin No. 42* upon this subject recently published by the Engineering Experiment Station of Purdue University.

Table I of the paper indicated the protective features of normally-operating arresters with several makes of transformers. It should be noted that the arrester connection used was equivalent to the use of the interconnection in service, and that under this condition, a good protective factor of safety was obtained even with some of the older-style dirt-covered transformers.

Data were presented in the paper on the wet and dry, surge and 60-cycle flashover values of the bushings of various makes of transformers. It is believed that data of this type, although known to manufacturers, are helpful to and desired by the various operating companies, which are not usually in a position to be well informed on the comparative merits of various transformers. Such, therefore, was the principal purpose of this paper.

**R. W. Weiseman:** The limitations of protecting a machine with a series inductance at the machine terminals as outlined by Mr. E. M. Hunter are in agreement with our paper.

Messrs. Palueff and Treat emphasized the need of machine protection even though the machine is insulated from the line by a transformer. In fact as we look back over the past performance of machines that we thought were protected by transformers, it was perhaps more good luck than good management that more failures on these machines were not encountered.

With reference to Mr. J. F. Calvert's questions in regard to the impulse test data, tests were made on machines with the rotor in the stator and with the rotor out of the stator. All tests were made on machines with multiturn coils. The voltage of the machines tested included the complete range of machine voltages and the slots of the machines did not have similar proportions. We are not in agreement with Mr. Calvert's statement that the transmission line theory will give moderately accurate voltage data at the ends of the winding, but no accuracy at all for other points in the winding. The voltage to ground taken at regular intervals along the winding by a cathode ray oscillograph proved conclusively that the errors involved in this method of calculating the voltage to ground are very small.

In conclusion we emphasize the fact that the benefits of rotating machine protection will be realized only when the protective equipment is installed with the machine. In other words, we can't expect protective apparatus to rejuvenate an armature winding after it has been subjected to and perhaps weakened by surge voltages for a number of years.

# Recommendations for Impulse Voltage Testing*

***Synopsis.**—Much of the data on impulse voltage testing of insulators and insulation which has been given out in the past has been obtained on a basis that renders it of little value for purposes of comparison and coordination. To clarify this situation the lightning and insulator subcommittee of the A.I.E.E. power transmission and distribution committee has conducted a study, the results of which are reported in this article. In this report the committee: outlines the present status of impulse voltage characteristic data for insulation; recommends a set of preferred test waves for laboratory use, discussing the use of these waves and test procedure with a view to obtaining comparable and coordinated characteristics of insulation; points out some of the limitations in securing impulse voltage characteristic data, and in the effective use of this data; and indicates the necessity for obtaining impulse data on a logical, accurate, and common basis, pointing out the benefits to be derived therefrom.*

* * * * *

IMPULSE flashover data on insulators, which some 10 years or so ago could be secured in only 1 or 2 laboratories, today are obtainable in some 6 or 8 laboratories in this country. In addition at least 2 electric utilities now own and operate their own lightning generators. With this increase in the number of lightning laboratories, it was found that the data obtained and given out were not comparable, apparently because of the different types of lightning generators and circuits employed and the varying test conditions and setups, and particularly because of the different shapes of the impulse waves employed. These varying data were interesting so far as they showed that the impulse voltage characteristics of insulators were different from the 60-cycle voltage characteristics; however, the major possible benefit that might have been obtained from such data was vitiated because the data could not be applied directly in any design or application work, since no means of checking or determining their accuracy and reliability were available. Practically no 2 sets of data from 2 different laboratories were obtained on a common and comparable basis.

Intensive field research on natural lightning and the invention of the cathode ray oscillograph made possible 2 things:

1. Approximate determinations of the voltage wave shapes produced on transmission lines by natural lightning.
2. A determination in the laboratory of both the actual shape of the applied voltage wave and the point on the voltage wave where insulation breakdown occurs.

Both of these factors, wave shape and point of breakdown, or time, must be considered to obtain a complete and effective application of impulse test data.

It is now known that the polarity of the impulse wave, barometric pressure, and also the humidity of the air, affect the insulator impulse sparkover; it is known further that these factors affect different types of insulators to a different degree. While in some cases these factors have small influence on sparkover values, the effect may be great enough to prevent successful coordination or grading of insulation within practical and economical limitations, if the variations are not considered and properly allowed for.

## PREFERRED TEST WAVES

It must be evident from the foregoing, that present data on impulse characteristics of insulators, protective gaps, etc., are available in such an incomplete form that they cannot readily be applied and used by those responsible for the design and successful operation of transmission and distribution systems and associated apparatus. It is the hope of the committee that the test waves and test procedure recommended here will be adopted generally, and will result in more rapid progress being made in the future in the accumulation of impulse data on a common, accurate, and comparable basis. It is hoped that this in turn will make possible the intelligent utilization of these impulse data in the art of generation, transmission, and distribution of electric energy so that both the power industry and the industries associated with it will benefit.

In order that the lightning flashover and puncture strengths of insulating members may be determined properly, the following are required:

1. Impulse test waves of definite and known shape.
2. The use of a sufficient number of wave shapes to allow lightning conditions in the field to be simulated at least approximately.
3. The use of wave shapes reproducible in laboratories within reasonable limits.

This committee recommends, therefore, that as far as possible, the impulse strengths of insulating members be determined from tests made with the following 3 wave shapes:

1x5 μsec        1x10 μsec        1½x40 μsec

The first number in each designation indicates the length of the wave front in microseconds measured from zero voltage to the crest of the wave; the second number is the designated length in microseconds measured from zero voltage to that point on the wave tail at which the voltage is equal to *half* crest voltage. The reasons for designating that both the fronts and lengths be measured from zero voltage are: (1) the usual equations for impulse circuits determine time from the zero point; and (2) so that a common basis of reference may be established. The 1x5-μsec wave is recommended to replace the ½x5-μsec wave recommended in the 1931-32 report of this committee because of difficulties encountered in securing the ½x5-μsec wave in all laboratories.

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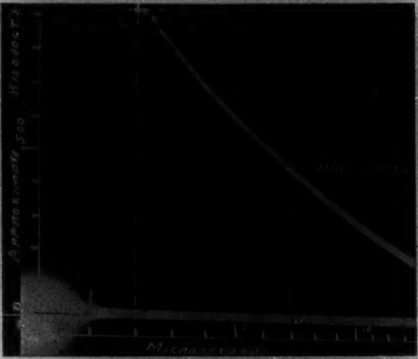
*A report prepared by the lightning and insulator subcommittee of the A.I.E.E. power transmission and distribution committee.

Lightning and insulator subcommittee: Philip Sporn, *chairman*; W. W. Lewis, J. J. Torok, J. T. Lusignan, K. A. Hawley, H. H. Spencer, I. W. Gross, H. L. Melvin.

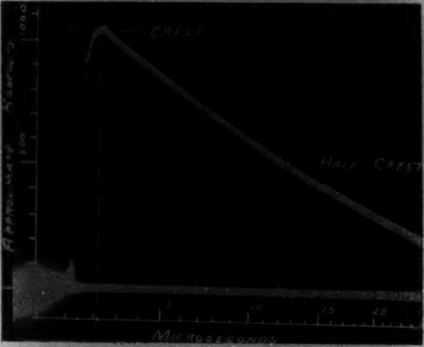
*Presented at the winter convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

Field records have shown lightning waves to have fronts and lengths varying over an extremely wide range; it is believed, however, that the 3 recommended wave shapes cover a range sufficiently broad to meet, as well as is practicable in the laboratory, the requirements for determining insulation breakdown characteristics for natural lightning. The committee does not recommend that every laboratory impulse test be conducted with all 3 waves, but that when test waves are being selected, preference be given to one or more of these 3 so that the results can be compared and used on a common basis. In choosing these 3 waves, consideration was given as to whether or not they could be produced satisfactorily and consistently in the various laboratories. Wave fronts shorter than one microsecond have been used in the past, but it was felt that one microsecond should be the established lower limit. The reason for this is that while satisfactory wave fronts of a fraction of a microsecond can be produced at the lower voltages, it is practically impossible to secure them at the upper voltage limits of some of the present-day lightning generators. The ability to impose a potential of several millions of volts upon a test piece and its lead from the lightning generator within a fraction of a microsecond without excessive and indiscernible oscillations can be questioned. The insertion of series resistance in the test circuit to check the oscillations results in lengthening the wave front to the order of a microsecond, and sometimes even longer. Because of the decreased damping effect of the high shunt resistance required for the longer waves greater series resistance is necessary to prevent oscillations on the front and crest of the wave. It is for these reasons that the 1½-μsec front was chosen for the 40-μsec wave.

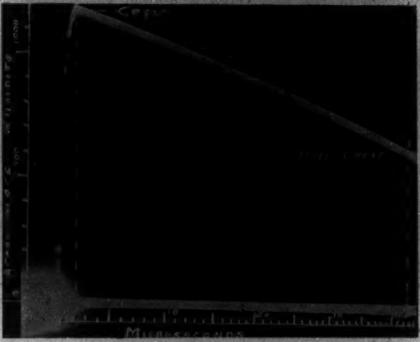
The wisdom of suppressing wave front oscillations in the manner indicated might be questioned by some, because in some cases lightning surges themselves may lack the proper circuit constants to eliminate oscillations on their fronts. In the laboratory, however, while it is essential to simulate lightning wave shapes as closely as possible, it is equally important that definite test waves be adopted which can be reproduced, measured, and recorded with reasonable accuracy. Not only are impulse waves with imposed oscillations of an appreciable magnitude difficult to duplicate consistently even on the same impulse generator, but also sphere gap measurements and oscillographic reproductions of such waves taken



1,000-kv 1 x 5-μsec wave



1,050-kv 1 x 10-μsec wave



1,200-kv 1½ x 40-μsec wave

These oscillograms have time to half crest voltage indicated from the crest, rather than from the zero point as recommended by the Committee

FIG. 1—OSCILLOGRAMS OF WAVES SIMILAR TO THE 3 RECOMMENDED WAVES, AS OBTAINED IN A TYPICAL LABORATORY

on the low voltage taps of potentiometers usually involve serious inaccuracies.

In recommending the 3 preferred test waves it has been necessary to compromise between the steepest and longest-tailed lightning waves so far observed on transmission lines, and the waves that can be obtained practically on insulation in a laboratory. That the recommended waves can be obtained in the laboratory is shown by actual oscillograms of impulse waves reproduced in Fig. 1. Similar waves have been obtained in other recognized laboratories. In Figs. 2, 3, and 4 are shown, in full lines, the 3 recommended test waves calculated from the circuit constants of the lightning generator. The dotted lines show the same 3 waves obtained by joining with straight lines the points actually specified in the definition of the waves.

Impulse wave shapes proposed or recommended by other A.I.E.E. committees also have been considered in an attempt to coordinate the several test waves in use. The transformer subcommittee of the electrical machinery committee has selected tentatively a 1½ x 40-μsec wave for impulse tests to be applied to transformers. (See progress report on *Impulse Testing on Commercial Transformers*, by Vogel and Montsinger, p. 409 of this issue.) Impulse waves recommended for lightning arrester testing by the lightning arrester subcommittee are defined both by rate of rise of the front and also by their ability to produce current through the arrester after the arrester comes into action. Such impulse waves cannot be used to give the desired information in insulator testing because: first, the voltage characteristics of the tail of the wave are not defined (tail of wave sparkover is an important factor in insulator testing); and second, it is impractical to obtain in the laboratory a constant rate of voltage rise, as the crest voltage of the test wave is altered successively in testing various types and sizes of insulators.

It is evident from the foregoing that the 3 preferred test waves recommended have been coordinated so far as is possible and practical with:

1. Natural lightning effects on transmission systems.
2. Reproducibility of these test waves in the laboratory.
3. Test waves proposed for impulse testing by other A.I.E.E. committees.

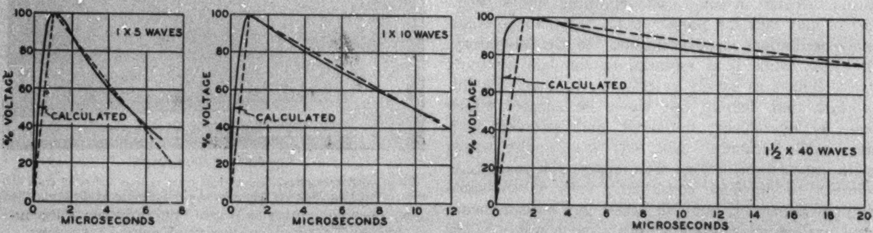
### TECHNIQUE AND PRECAUTIONS IN IMPULSE TESTING

Although the 3 wave shapes recommended are defined simply by front and tail characteristics, some difficulties may be met in producing them in the laboratory and in applying them to test work, if considerable care and precautions are not taken. The subject of impulse testing technique was discussed in 2 papers in 1932: *Characteristic of Surge Generators for Transformer Testing*, by Bellaschi, A.I.E.E. paper No. 32-87 and "Impulse Testing Technique," by Foust, Kuehni, and Rohats, *G.E. Review*, v. 35, p. 358, 1932. Two additional papers were presented at the 1933 A.I.E.E. winter convention: *Laboratory Measurement of Impulse Voltages*, by Dowell and Foust, page 537 of this issue; and *Measurement of High Surge Voltages*, by Bellaschi, page 544 of this issue. The lightning and insulator subcommittee commends the full and frank presentation of such discussions.

It is recognized that conditions under which the various laboratories must work are not at all identical, and that improvements constantly are being made in testing apparatus and methods. This committee, therefore, does not contemplate the standardization of test equipments, circuits, or methods. Rather, it is intended that the design and selection of testing equipment, the analysis of discharge-circuit current and voltage conditions, and the selection of test methods, be placed on such a basis as to leave no doubt that conditions of voltage application to the sample being tested are known thoroughly and are demonstrable. For this purpose the following recommendations are made:

### TESTING RECOMMENDATIONS

1. Use only testing equipments and circuit arrangements that can be analyzed readily as regards the location and amounts of capacitance, inductance, resistance, and conductance constants present, all of which have an appreciable effect on the shape of the voltage wave applied to the test specimen.
2. Measure with reasonable accuracy such circuit constants as indicated in item 1.
3. Calculate voltage wave shape at the sample under test.
4. Take cathode ray oscillograms of wave shapes applied to the sample under test.
5. Compare the calculated voltage waves with the waves obtained in oscillograms.



FIGS. 2, 3 AND 4.—THE 3 RECOMMENDED IMPULSE VOLTAGE WAVES AS CALCULATED FROM THE CONSTANTS OF THE LIGHTNING GENERATOR. DASH LINES HAVE BEEN DRAWN THROUGH THE POINTS SPECIFIED IN THE DEFINITION OF THE WAVES

6. Adopt such testing technique as is best suited to the testing equipment being used and the sample being tested.

7. Include with test results all details regarding each of the previous 6 items, such as will bear full evidence that testing conditions are thoroughly known and fully demonstrable.

8. Wherever possible, make impulse tests with both positive and negative applied voltage.

### MEASURING SPHERE GAP

The measuring sphere gap, which commonly is used as the primary standard for determining the applied impulse voltage, should be selected in accordance with A.I.E.E. STANDARD No. 4. These standards apply to spheres up to 750 mm in diameter and to rms voltages up to 900 kv. At present there are no agreed-upon standards for spheres larger than 750 mm, although in several laboratories such spheres are in use and higher voltages are being measured by reference to calibration curves from different sources. It is recommended that the appropriate Institute committee take steps to extend the sphere gap calibrations.

### STANDARD TEMPERATURE, PRESSURE, AND HUMIDITY

All test results obtained under prevailing temperatures, barometric pressure, and humidity conditions, should be corrected to the following standard conditions:

| | |
|---|---|
| Temperature | 77 deg F (25 deg C) |
| Barometric pressure | 29.9 in. (760 mm) of mercury |
| Humidity | That corresponding to a vapor pressure of 0.6085 in. (15.45 mm) of mercury (65% relative humidity at 77 deg F, and barometric pressure of 29.9 in.) |

Sphere gap and sparkover voltages should be corrected to standard atmospheric conditions of temperature and pressure by the use of the air density correction factors given in A.I.E.E. STANDARD No. 4. It is assumed that there is no humidity correction for sphere gaps.

The test piece flashover voltage should be corrected to standard atmospheric conditions of temperature and pressure by the use of the relative air density correction factors given in A.I.E.E. STANDARD No. 4. Although air density correction factors would be somewhat more accurate, such factors have not been established for the various types of insulators and gaps.

Humidity correction, based on vapor pressure as discussed in A.I.E.E. STANDARD No. 41, must be determined from data accumulated on different types of insulators and gaps. Since correction factors for humidity are not now generally available for impulse voltages, it is recommended that a record always be made of the existing humidity, so that later the data may be corrected to a standard humidity condition.

### TOLERANCES OF MEASUREMENTS

Since the practical application of impulse data on insulation involves, in most cases, the accuracy of the measurements, it is important that the possible and probable limits of this accuracy be known. It is recommended, therefore, that all impulse test data be accompanied by a statement of both the estimated possible and probable errors in magnitudes of voltage and time.

At present it is believed that discrepancies in the average sparkover voltage as obtained in different laboratories may be as great as 20 per cent on tests made with the short wave, and 5 per cent with the two longer waves; also in any one laboratory individual values vary ± 5 per cent from the average values. A better understanding and application of laboratory technique and test equipment promises, for the future, an appreciable reduction in these overall tolerances.

### PRACTICAL APPLICATION OF IMPULSE DATA

The purpose of obtaining flashover characteristics of any insulation is, of course, to determine its electrical strength. In the past the electrical strength of insulation has been judged by its 60-cycle flashover voltage. To-day it is recognized that lightning or impulse surges cause the greatest number of line flashovers; therefore, it is important to know the impulse flashover characteristic of the insulation.

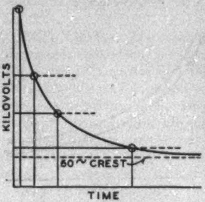


FIG. 5.—VOLT-TIME FLASHOVER CHARACTERISTIC OF INSULATION FOR A THEORETICAL SQUARE-FRONT FLAT-TOP WAVE

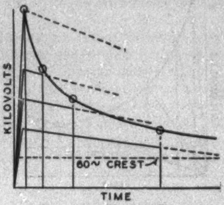


FIG. 6.—VOLT-TIME FLASHOVER CHARACTERISTIC OF INSULATION FOR A PRACTICAL SQUARE-FRONT FLAT-TOP WAVE

One of the chief uses of information on the impulse flashover of insulators is for comparison purposes in the choice of insulation for proper coordination. Exact impulse characteristics of the insulation must be known if proper levels of insulation are to be established. To coordinate insulation properly throughout the entire range of impulses which might appear in practise, it is necessary to know more than the flashover value of the insulation at one point of one particular impulse wave.

At present, there are several ways of obtaining a nearly complete picture of the impulse characteristics of insulation. One of the most desirable of these is by determining what may be called the volt-time characteristic of the insulator. Volt-time characteristic curves may be obtained by applying an impulse potential across the insulator and determining the time required for flashover. Succeeding applications of voltage are made with different crest voltages, the time to flashover being determined for each application. The crest value of impressed voltage and its corresponding time to flashover then is plotted as shown in Fig. 5.

While theoretically this method of obtaining volt-time curves is highly desirable, it is impractical because in any laboratory where cost of equipment is a factor, it is impossible to obtain a square front flat top wave. However, the type of curve shown in Fig. 5, may be approximated by impulse waves, such as those shown in Figs. 6 and 7. In Fig. 6, a single wave shape is used at different amplitudes and all breakdowns are on the tail of the wave. In Fig. 7, all breakdowns are taken on uniformly rising wave fronts, the front being changed for each voltage application.

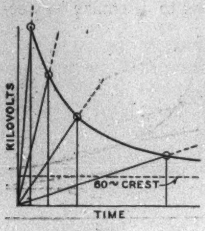


Fig. 7. Volt-Time Flashover Characteristic of Insulation With Breakdown on Front of Wave

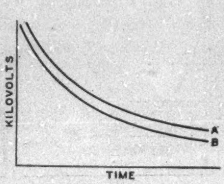


Fig. 8—Typical Flashover Characteristics of 2 Coordinated Insulating Members

Another way of obtaining impulse characteristics of an insulator over wide ranges of time is to use waves of different shapes and determine by repeated application the minimum voltage which will just cause sparkover. This is called the minimum wave, 50-per cent sparkover method, that is, the minimum voltage which on being applied to the insulator, will cause sparkover half of the time. This method could well employ the 3 test waves recommended in this report, and does not require the continuous use of an oscillograph. The method becomes more accurate as the number of waves is increased.

It must be recognized that characteristic curves obtained by the 2 methods described are not comparable; that is, data obtained with the 50-per cent sparkover method will not have the same characteristics as data obtained with the methods illustrated in Figs. 6 and 7. At present, laboratory data available are insufficient to allow greater significance to be attached to one of these methods rather than to any other. Sufficient data should be obtained by the different methods to permit definite conclusions to be drawn as to the value of each method.

A survey of data already accumulated indicates that considerable information is available regarding the impulse flashover characteristics of various types and forms of insulation. However, a large part of the data has been obtained either by methods now obsolete or on a basis which would not be comparable with the methods outlined here, and particularly on a basis such that data obtained in different laboratories are not comparable. Only in the past year or so can data published by the more important laboratories be used for insulation coordination, and then only on that particular basis on which the data have been secured.

For the foregoing reasons it is essential that impulse data be obtained on some fixed basis for apparatus such as insulators, bushings, gaps, and other insulating members. This fixed basis may well take the form of a volt-time curve such as those illustrated in Figs. 6 and 7. However, it is clear that the obtaining of comparable data on these bases requires the use of a definite wave or group of waves.

Since both positive and negative waves are found on transmission lines, it is important in the laboratory to obtain impulse data for both polarities. Much of the earlier impulse data have been obtained without particular regard to polarity; consequently, the averaged values may lie between the positive and negative flashover values of that insulation. More recently testing has been done on a basis in which only one wave is used, either the positive or the negative. Since it was recognized that the positive impulse sparkover voltages were lower than the negative, it was decided to obtain the impulse information by using principally the positive wave. For complete and reliable coordination, however, it is necessary to have both positive and negative volt-time curves of all of the insulation involved.

For comparative purposes throughout a wide range of possible impulse voltages found in practise, the volt-time characteristics of an insulator give the most complete and therefore the most desirable information. By the use of these curves the relative behavior of 2 pieces of insulation subjected to impulse voltages can be predicted. For example, one form of insulator may have a characteristic curve as shown in curve *B* of Fig. 8, and a bushing may have the curve *A* characteristic; if the insulator and bushing are connected in parallel, the insulator will flash over, on the application of an impulse voltage, rather than the bushing. Predicting insulation breakdown on this basis is the ultimate aim of impulse testing. By this method the location of flashover of insulation can be controlled.

Coordination of insulation on the above basis may be expected to result in advantages as follows:

1. Protection of expensive and important apparatus against the effects of lightning should be more complete than at present, even where lightning arresters now are used.
2. Greater economy of system design should be possible without the danger of subjecting valuable apparatus to breakdown from lightning.
3. Lower maintenance costs on station apparatus subject to the effects of lightning may be expected, since it should be possible to prevent destructive impulse voltages from reaching that apparatus.
4. Electric service as a whole should be improved, since by insulation coordination, it should be possible to control the location of lightning flashover on the system so as to result in a minimum of damage and service interruption.

## CONCLUSIONS

Important points brought out in this report and recommendations made by the lightning and insulator subcommittee may be summarized as follows:

1. Impulse voltage characteristic data on insulation which have been obtained in various laboratories up to the present time, have been on such widely different bases that the effective use of this data has been almost impossible.
2. The committee recommends 3 preferred impulse test waves, 1 x 5, 1 x 10, and 1½ x 40 μsec, the use of which in all laboratories should result in comparable data being obtained on impulse characteristics of insulation.
3. That these recommended test waves actually can be produced in practise is demonstrated by the group of laboratory test waves, oscillograms of which are reproduced in this report.
4. To insure insulation actually being subjected in the laboratory to impulse voltages of known characteristics, a group of general recommendations for laboratory procedure have been made by the committee.
5. It is recommended that, wherever possible, oscillograms of the actual impulse wave or waves applied to insulation be obtained at the time of test.
6. For the intelligent application of impulse data in actual practise, tolerances or accuracies obtainable in laboratory measurements should be taken into account. Failure to do so may affect greatly the successful coordination of insulation on an electric system.
7. Complete information on the impulse characteristics of all insulating members of an electric system is necessary for proper coordination of insulation. This information is desirable in the form of volt-time curves, types of which are illustrated in this report.

It is hoped that the recommendations made in this report will offer a basis for more rapidly advancing the art of satisfactory insulation coordination on the impulse basis so that all possible economies in the design of electric systems and improvement in the service supplied by these systems may be actually realized.

## Discussion

**A. O. Austin:** There are so many factors involved which affect the flashover values obtained under an impulse that the committee has done much in obtaining a fairly uniform agreement as to results from most of the laboratories. The difference in equipment and the difficulty of obtaining uniformity with certain types of waves make it necessary that comparisons be made with waves which can be produced and which will give fairly uniform results in the various laboratories. Unless this can be done of course comparisons cannot be made with any degree of certainty. However, it must be recognized that in operation a direct hit usually results in a very steep front in the immediate vicinity. Unfortunately impulses of this type are attended with oscillations and are more or less difficult to analyze and compare.

Many systems probably do not have conditions imposed upon the equipment having any steeper fronts than the waves proposed. However, it will be found that protective apparatus must take into account waves of steeper front if protection is to be provided for direct hits in the immediate vicinity. A protecting gap which will provide protection to a bushing, bus insulator or other piece of insulation with wave fronts of 1 to 1½ microseconds may have to be very materially reduced in order to provide protection for a direct hit in which the wave fronts may be very much less. In providing protecting equipment the flashover values and time lags may be quite different for the positive and negative impulses, hence the protecting gap should be adjustable so as to take this into account if protection is to be provided with a minimum of tripouts.

It has been more or less common practise to equip bushings so that a discharge point or electrode could be attached to the top for reducing the flashover voltage on positive impulse and a discharge point applied at the flange to control the flashover under negative impulse. A protecting gap which can be adjusted not only to change the time lag but to regulate the time lag and flashover voltage for negative and positive impulses was presented in a paper before the A.I.E.E. at the Milwaukee meeting in 1932[1].

**F. D. Fielder:** The committee has recommended two general schemes for laboratory testing: the use of minimum flashovers on three different waves, and the use of time lag curves obtained with a long wave. It is noteworthy that besides showing insulation characteristics more completely, the time lag curve method is becoming more generally used. It seems logical that the use of three different shapes of waves be eliminated to conserve laboratory time, especially since it is possible that minimum flashover values with waves of different tails can be obtained from specific points of the more complete time lag curves. It is noted that volt-time curves are described for cases where the breakdown occurs on the rise of the wave. Those with laboratory experience will agree that this type of test is impractical at very high voltages, because of insulation difficulties with high voltage inductances. This method is not widely used at the present time for this reason.

We neither approve nor care to accept the enumerated testing recommendations. Such a method is laborious, and certainly not conducive to precise impulse measurements. Calculations may have certain value, but when they have been once used to show the proper operation of the circuits, it seems needless to repeat them for every change of apparatus. In addition there is some question as to how rigorous methods of calculation should be.

We also do not agree with the proposed use of the sphere gap as a primary standard. Although A.I.E.E. Standard No. 4 gives curves for spheres up to 750 mm, these curves apply only for commercial voltages, and they have not been experimentally checked for surges. Careful investigation shows that the curves do not check each other in parallel surge tests, and that positive and negative surge calibration curves differ.

Peek has clearly defined the ½/5 wave as meaning a ½ microsecond front and a 5 microsecond tail[2]. We also have used this designation for a number of years. There is no apparent advantage in changing. The shorter wave resulting from the definition proposed by the committee will mean greater surge generator regulation. Also with this new wave, apparatus will have higher flashover voltages. Both factors decrease the apparatus testing range of a given surge generator. This point is very important when it is necessary to use several hundred ohms series resistance to secure a reasonably smooth wave. For these reasons we do not approve of the change.

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[1] *An Improved Type of Limiting Gap for Protecting Station Apparatus* by A. O. Austin, A.I.E.E. TRANS., Sept. 1932, p. 676

[2] A.I.E.E. TRANS., October, 1930, p. 1460

The most pressing question regarding surge tests is the disagreement in reported results from the different laboratories. It is believed that these differences should be the object of immediate study. Rather than devise test codes and procedures and schemes for collecting data, there should be further concentrated study of the fundamentals of the problem.

**C. L. Fortescue:** There is need for comment on the recommendations for impulse voltage testing put forward by the Lightning and Insulator Subcommittee. The three standard waves chosen are satisfactory for laboratory testing and are fairly representative of types of waves that may be expected to enter a substation connected with transmission lines. Where it is desired to find out the effect of very steep waves on insulators, gaps, and so forth, this can readily be done using a powerful surge generator by removing the damping resistors and applying the full value of the surge to the insulator string in which case flashover will take place on the front of the wave at a low time lag and high impulse factor. Here the slope of the wave is of primary importance. The effect of oscillations which appear at the crest and tail of the wave are eliminated. The writer comments as follows on the proposed testing recommendations: The calculation of the shape of the voltage wave applied to the test specimen always is worth while but it should be recognized that even for the simplest circuit the solution at best is approximate. A rigorous solution is extremely difficult and the time required to carry it out would make it impracticable. In the writer's opinion the cathode ray oscillogram used in connection with a reliable voltage divider is the best method of measuring the impulse voltage required to break down the piece under test and the time lag. There is some question as to the calibration of the sphere gap, except for gap settings less than the radius of the sphere.

The writer regards the impulse time lag curves of insulators and spark gaps as giving their fundamental breakdown characteristics under surge conditions and has found that these curves can be used very effectively in determining the length of insulator strings, tower clearances, and ground wire to line wire spacings for the types of waves encountered when ground wires or towers are struck by lightning. It would be desirable to obtain these impulse time lag curves by using a wave more nearly approximating a perpendicular flat topped wave. If the importance of the volt-time lag curve had been recognized at the start, means might have been developed to obtain a more desirable wave for this purpose. However, the 1½-40 wave gives good practical results though the impulse ratios at the shorter time lags show up high since breakdown takes place at the front of the wave. It is not difficult to make allowance for this, at least for such approximate calculations as are used in estimating the protection level of transmission lines. It is important that the laboratories should be encouraged to develop their technique in obtaining voltage time lag characteristics of insulators and spark gaps for these are fundamental data.

The data obtained by the several laboratories are now fairly complete. A good part of these data secured by one of the laboratories is presented in the paper by Messrs. Montsinger, Lloyd and Clem (see page 417). An examination of these data will show, compared to Westinghouse data, that the correspondence is very close on the long wave impulse time lag curves but not so good on the short wave impulse time lag characteristics. It seems that the long wave testing gives less chance for variation due to technical differences in the various laboratories. In my opinion impulse time lag characteristics will give sufficient data for practical use in coordination of insulation.

**C. M. Foust:** In spite of dealing with a rather difficult subject the committee has produced a report which is factually sound, comprehensive and forward looking. In submitting a word of caution regarding volt-time breakdown curves, the writer believes that the so-called minimum wave flashover volt-time curve as shown in Fig. 6 has been credited with a wide significance that cannot be demonstrated by existing data regarding practical operating conditions or the mechanism of insulation breakdown. Coordination of insulations on the basis of volt-time data from wave tail flashovers should be accepted as applying only to field conditions where the incoming waves are of just sufficient voltage amplitude to produce wave tail flashover. The same time-voltage relationship does not hold for other conditions of voltage application such as wave front breakdown as shown in Fig. 7.

Apparently it is necessary to consider two general factors when tests are being planned for the purpose of working out insulation coordination. The first of these factors has to do with wave shapes found in operation, on which shapes coordination is necessary, and the second with the mechanism of breakdown of the insulations being coordinated.

Regarding waves in power circuits, available data indicate that a wide range of shapes are present. Steep front waves of high voltage amplitude giving breakdown on the wave front, as well as low voltage sloping front waves, have been recorded; in each particular case where coordination on the front or tail should be considered. Also it may be desirous in some cases to coordinate on all three recommended waves allowing breakdown to come on the front, crest or tail as the mechanism of breakdown of the insulation determines.

The second general factor of importance, mechanism of insulation breakdown, has not received the attention it should. Consider for instance the case of two insulations each having about the same minimum wave crest voltage breakdown, each having definite impulse ratios but one breaking down on the wave tail and one on the wave crest. This is not an imaginary circumstance. In general insulators flashing over through long arcs, or breakdown over solid insulation surfaces where long creepage streamers are formed give wave tail breakdown. In this case the usual minimum wave tail breakdown volt-time curve is obtainable. But through breakdown of solid insulation, short arcs through oil, vacuum or other insulations in general do not give wave tail breakdown although they do have high impulse ratios. Here the minimum wave, tail breakdown, volt-time curve is *not* obtainable.

The long arc breakdown giving wave tail flashover should be regarded as a volt-time phenomenon somewhat on the following basis: The streamer bridging between the two electrodes grows in length at definite rates depending upon the overvoltage applied. With a flat topped wave adjusted to critical breakdown value the streamer tip velocity is low and the large time element required for its formation therefore easily measurable. With a decreasing voltage on a wave such as the (1½-40) a higher crest voltage is required than for the square topped wave and the time elements are shortened somewhat although still of appreciable magnitude to permit good measurement. Flashover in this case is a race between the decreasing velocity of the streamer tip and the falling voltage behind the streamer.

Obviously when insulations having such radically different mechanisms of breakdown are to be coordinated a careful study of the nature of breakdown is required if great confidence is to be had in the arrangement decided upon.

Factual matter such as touched on briefly in this discussion must carefully be considered for future work. Good progress will be achieved by careful planning of investigational work in the field and in the laboratory. This planning must be directed toward the securing of information which will inspire confidence in the significance of laboratory tests. Large expenditures directed solely toward the accumulation of more of what this committee rightfully classifies as "obsolete data" are not desirable. Careful scientific research work directed toward a clarification of the problem at hand is most necessary.

**K. A. Hawley:** It may be well to point out just why it is desirable to make impulse tests with both positive and negative waves. If there were in all cases a constant percentage of difference between the positive and the negative flashover values then a measurement with one polarity would be all that is required for coordination purposes. Actually the percentage of difference between positive and negative values varies considerably with different insulators. The limits of this variation with the usual commercial insulators and gaps is not definitely known at this date. There are some known cases, however, in which the negative wave flashover of one insulator has been more than 30 per cent higher than the positive wave flashover, while the flashover value of the coordinating gap has been almost the same for both positive and negative waves. Obviously in such cases if the flashover measurements for coordination had been made using a negative wave only, then satisfactory coordination would not be obtained for positive waves. It is perfectly conceivable that in some other cases coordination established using only a positive wave may not be obtained when a negative wave is used.

In connection with Fig. 8 it should be noted that these curves need not always be parallel as shown. In fact in many cases there is a great difference in the slope of the volt-time curves for different insulators and gaps. If curve *B* happened to be steeper than curve *A* and crossed curve *A*, then although satisfactory coordination would be indicated by tests using the "minimum wave" or "50 per cent sparkover" method still when higher voltages were applied the coordination would be destroyed. Since the maximum expected wave on a transmission line usually will be considerably above the flashover value of the insulators involved in the coordination, it is apparent that some knowledge of the volt-time curves is essential.

**K. B. McEachron:** From the point of view of protecting insulation from flashover due to direct strokes it is necessary to give consideration to the front of the wave flashover. A very large proportion of direct strokes apparently have sufficient potential available to flash over the usual insulation strengths on the front of the wave. The tail of the resulting traveling wave will depend upon the form of the current wave of the direct stroke and the tower footing resistance.

The present proposed standards for testing lightning arresters referred to in the committee report were intended to furnish data from which comparisons of arresters could be made, but not necessarily to represent performance in service.

It is possible to make tests on lightning arresters using the three waves proposed in the report, but to obtain appropriate current waves the test should be made on a transmission line. Under such a condition the current is related to the potential of the traveling wave and the rate of current rise is the same rate which would have been obtained with natural lightning of the same wave shape. On the transmission line when the potential is a maximum the current is also a maximum, but in the laboratory this relationship is in general not readily obtainable. Since the test on a transmission line is expensive, the lightning arrester subcommittee did not propose its use, although the day may come when it will be feasible.

Oscillograms are available showing the performance on thyrite arresters on a transmission line of the Consumers Power Company taken in 1930. Such records show the exact performance of the arresters under conditions obtaining in service.

Lightning arresters must operate on the front of the wave and therefore the rate of rise is important in determining the potential at which the arrester begins to carry current with different wave fronts applied. Once the arrester becomes conducting, the only effect of the tail of the wave is to determine the magnitude and form of the current wave through the arrester.

When testing insulators only the potential wave is of importance, which accounts for the difference between the arrester proposed standard tests and those suggested by the committee.

**H. K. Sels:** Referring to the subcommittee's recommendation for impulse voltage testing, Mr. Alger has called attention to the limitations of such standard waves in the testing of rotating machinery which the writer believes may also be true of other equipment, particularly lightning arresters. With lightning arresters, it is desirable to have them discharge as soon as possible under impulse voltages and maintain as low a terminal voltage as possible while the discharge is taking place. Therefore, while initially voltage conditions prevail, after the discharge starts, the current conditions are the criterion for determining the resulting arrester voltage. Hence, a different sort of specifications than those proposed are necessary.

Two years ago, the subcommittee on lightning arresters recommended impulse waves for testing station type arresters above 15 kv with a voltage rise of 100 kv per microsecond per 11.5 kv of arrester rating and after the beginning of discharge with a current rise of 150 amperes per microsecond to a crest of 1,500 amperes. Other variations in the wave are also given for lower voltage ratings and line type arresters. It is believed that with the present limitations in test equipment, these tests are adequate for comparative purposes, although no indication is given of the protective capabilities of the arrester to protect equipment under service conditions. Whether traveling wave conditions with both voltage and current waves also are necessary in the testing of other equipment is a problem which should be considered by the subcommittee.

**F. J. Vogel:** The report is very valuable, furnishing a standardization of the test waves and an interpretation of the test results. However, the specifications for the procedure of tests in the laboratory, under the heading "Testing Recommendations," are unnecessarily complicated. In a properly standardized laboratory, it should be possible to analyze once and for all the performance of the surge generator and to demonstrate the accuracy of the cathode ray oscillograph and divider. For example, the work done in Sharon in analyzing the performance of the surge generator was presented to the Institute at Cleveland in June, 1932, by Mr. P. L. Bellaschi[3] and furnished the first known published analysis of a surge generator circuit to take account of the stray generator and load capacity. The work done at Sharon in calibrating the cathode ray oscillograph and its dividers is given in the paper by Mr. P. L. Bellaschi on page 544 of this issue. After this analysis and calibration have once been accomplished, it would seem that the use of such a calibrated system is in no way different in principle from the use of the more common indicating meter. In this case, there is no need of calibrating the meter for each individual test, but occasional checks are all that is required.

**P. L. Bellaschi:** Each of the main items treated in this report could well be made a subject of profitable discussion and critique. The question of measuring sphere gaps is particularly pertinent for discussion from a fundamental standpoint.

The subcommittee definitely accepts the present standard calibration curves of sphere gaps (A.I.E.E. Standard No. 4) for surge voltage measurement, and on this basis it considers the sphere gap as a primary standard for surge voltage measurement. It should be noted that these calibration curves were established for measurement of voltage at power frequencies. It is a simple matter to show that these calibration curves are incorrect for measurement of surge voltages. The issue of the matter is this: In the application of the sphere gap to surge voltage measurement, there is no fundamental basis to justify its use as a primary standard; in truth, it is a secondary standard. In surge voltage measurement, the sphere gap should therefore be calibrated, or better still, a resistance potentiometer used directly.

**Philip Sporn:** Since any group of impulse voltage test waves must of necessity be a compromise based on actual lightning waves on transmission lines, theoretical calculated waves, and waves which actually it is possible to produce in a practical laboratory, it is particularly gratifying to note from the discussions that the three waves recommended by the committee have generally been accepted not only as practical but also as adequately covering any reasonably possible voltage conditions which may be met with in practise.

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[3] *Characteristics of Surge Generators*, A. I. E. E. TRANS., December, 1932, p. 936.

Now that a uniform yardstick (that is, the three preferred test waves) has been established, it is believed that impulse testing has taken a decided step forward. There still remain, however, several problems in the production, application, and use of data secured by these test waves.

Mr. Fielder seems to have the impression that the committee has recommended obtaining impulse data according to two general schemes: first, obtaining minimum flashover with three different waves and, second, obtaining time lag data with the long wave. It should clearly be pointed out, however, that the committee at the present time has not made any recommendations on the type of impulse data to be obtained to the exclusion of any other type. As a matter of fact, the members of the committee at the present time are not in agreement that any one of the typical curves of impulse characteristics of insulation given in the paper will supply enough information properly to coordinate insulation strengths in a transmission system. Some members favor one type of voltage time lag curve and some another type; and it may be that the necessary complete picture of the impulse strength of insulation will be shown only when data are secured with all the different waves used in all the different manners indicated in the paper.

Mr. Fielder also is under the impression that there is no apparent advantage in measuring all times of impulse waves from the zero point of the wave. There are, in our opinion, however, two distinct advantages in measuring time from the zero point of the wave. The first is that there is less confusion in indicating time from a fixed point, one, such as the origin of the wave rather than from a reference point which is subject to some time variation as is the case with the crest of an impulse wave with varying load conditions on the generator. The second advantage is that since in the calculation of impulse wave shapes, all times are computed from the origin of the wave, there is less chance of error and misunderstanding if the start of the wave is used as a reference point. This matter was gone into thoroughly in the committee meetings and it was felt that every advantage was in favor of measuring time in all cases from the zero point of the wave rather than from the crest.

Another point on which discussion was raised was that of using the sphere gap as a measuring device for indicating the crest value of impulse waves. It is felt that it is much better, with our present knowledge of voltage measuring devices, to measure impulse waves with a standard such as the sphere gap rather than some other device which has not yet been thoroughly tested, proved, and accepted as a standard. It is readily appreciated, however, that with continued use, and a better understanding of factors influencing the ratio of resistance potentiometers they may well take their place along with the sphere gap or possibly replace it as a measuring device in impulse testing. Until such time, however, the evidence is not very conclusive that anything is to be gained by dropping the sphere gap as a standard of voltage measurement.

The discussions by Messrs. McEachron and Sels referring to the type or voltage waves recommended by the Lightning Arrester Committee for testing lightning arresters seemed to show quite clearly that the testing of lightning arresters and insulators cannot be coordinated by the use of one common impulse test wave at the present time, on account of practical difficulties in test circuits. Since the function of a lightning arrester is to get into action as soon as an excessive voltage appears on the line, and further to discharge the impulse current while holding this voltage to a safe value, it appears that any test wave for a lightning arrester should logically be based on the rate of voltage rise of the lightning wave and the ability of the wave to supply current through the arrester. The shape of the tail of the wave, therefore, is of importance only as it affects the supply of current to the arrester.

In the case of insulator testing, however, it is the voltage time characteristic of the wave throughout its entire duration which alters the insulation strength of the insulator. The current in the test wave does not affect the impulse performance of the insulator. It seems readily apparent, therefore, that any attempt to use the same impulse waves for testing lightning arresters and insulators will result only in a restriction of our knowledge of arrester performance and the ability of insulation to withstand flashover.

Mr. Hawley's discussion brings out clearly why it is necessary, in obtaining a more nearly complete picture of insulation strength, to test with both positive and negative impulse waves. Information on both polarity should, of course, be obtained for the maximum benefits to be secured in obtaining impulse characteristics of insulators. The excellent work that has been done during the past few years in analyzing the fundamentals of impulse testing in the laboratories has done much to place impulse testing on a more sound and rational basis. While there are still some points of disagreement, it is believed that if the various laboratories continue their efforts, that a common basis for conducting tests and reporting data can be reached which will be of great benefit to all who have occasion to deal with problems involving impulse strength and characteristics of insulation in all its varied forms.

# Lightning Investigation on Transmission Lines—III

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***Synopsis.**—The field data for 1931 and 1932 are reviewed, with especial reference to lightning stroke currents. When direct strokes take place to towers or ground wires, flashover occurs if the product of current and tower footing resistance is higher than the flashover strength of the insulators. Flashover seldom occurs if ground wires are present and the towers have low footing resistance.*

*Three years' records on four systems indicate tower currents varying from 1,000 to 150,000 amperes. Tripouts correlate almost exclusively with high tower leg currents of negative polarity, that is, the tower top is negative with respect to the base. This indicates that the severe lightning strokes come from negatively charged clouds. A great amount of experimental data, relating to flashover between electrodes of dissimilar shapes, are shown to be in accord with these field observations.*

## INTRODUCTION

THIS paper is the fourth of a series of A.I.E.E. papers by the same authors, giving the results of a lightning investigation conducted on a number of power systems, through the cooperation of the power companies and the General Electric Company. The previous papers[1] summarize the results for the years 1926 to 1930 inclusive. Certain theories as to the mechanism of the lightning stroke and the effect of polarity have been presented.[2]

The present paper will bring the information up-to-date and further discuss the theories of the lightning stroke mechanism.

The investigation was continued in 1931 and 1932 on the Pennsylvania Power and Light Company's 220-kv Wallenpaupack-Siegfried line, the Ohio Power Company's 132-kv Philo-Canton line and the Atlantic City Electric Company's 66-kv Deepwater-Pleasantville line, all of which have been described in previous papers.[3]

Work was started in 1932 on the 132-kv Glenlyn-Roanoke line of the Appalachian Electric Company. This is a double-circuit line, 65 miles long, similar in construction to the Philo-Canton line. Three areas on this line, which had been subjected to numerous flashovers in the years 1927 to 1931, inclusive, were selected for the investigation. These areas are designated: towers 6 to 22, inclusive, Roanoke end, towers 50 to 69, inclusive, Roanoke end, and towers 8 to 28, inclusive, Glenlyn end.

During 1931 and 1932, work with the cathode ray oscillograph was discontinued. Data were secured with the following instruments: *magnetic oscillograph, surge voltage recorder, severity meter, lightning stroke recorder* and *surge indicator.* A new instrument, the *surge crest ammeter,*[4] was introduced on a limited scale late in 1932, but practically no data were obtained with it in the time available.

A number of "lightning rod" installations were erected on each of the four lines under investigation. On the 220-kv line these consisted of iron pipe extending 30 feet above the top of the tower. On the 132-kv lines a copper conductor was used, extending 10 feet above the top of the tower. The pipe or conductor was connected to the tower through a 0.15-ohm resistance, shunted by a lightning stroke recorder.

The ground wires at the towers equipped with lightning rods were insulated from the tower and connected to the tower through a 0.3-ohm resistance, shunted by a lightning stroke recorder.

The purpose of the lightning rod instruments and ground wire instruments, in connection with the instruments on the legs of the towers, was to differentiate between the total stroke current and that flowing in the ground wires and in the tower itself.

TABLE I—LIGHTNING STROKE RECORDS—1931 FROM WALLENPAUPACK-SIEGFRIED 220-KV LINE. PRODUCT OF CURRENT X TOWER FOOTING RESISTANCE X $10^{-3}$

| | Accompanied by tripout | | | Not accompanied by tripout | | |
|---|---|---|---|---|---|---|
| Product | Number | Per cent | | Number | Per cent | |
| Less than 20 | 0 | 0 | 15.8 | 7 | 20.6 | 64.8 |
| 20— 100 | 3 | 15.8 | | 15 | 44.2 | |
| 100— 200 | 1 | 5.2 | 31.5 | 3 | 8.8 | 29.4 |
| 200— 300 | 2 | 10.5 | | 3 | 8.8 | |
| 300— 500 | 3 | 15.8 | | 2 | 5.9 | |
| 500—1,000 | 0 | 0 | | 2 | 5.9 | |
| 1,000—2,000 | 4 | 21.1 | 52.7 | 1 | 2.9 | 5.8 |
| 2,000—5,000 | 4 | 21.1 | | 1 | 2.9 | |
| Over 5,000 | 2 | 10.5 | | 0 | 0 | |
| | 19 | 100.0 | | 34 | 100.0 | |

Range of
Product—26 to 14,805
Current—2,000 to 115,000 amp

Range of
Product—2 to 2,530
Current—1,000 to 140,000 amp

In previous years, a great deal of data have been secured as to magnitude of voltage on transmission lines due to lightning and switching, shape of waves, attenuation, field intensity, storm severity, tripouts, flashovers, effect of ground wires, current in towers due to strokes, etc.

During the past two years, the investigation has concentrated on the measurement of tower currents, storm

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*General Electric Company, Schenectady, N. Y.

1. For references see end of paper.

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severity, tripouts, flashovers and the effect of ground wires. An effort has been made to formulate a rational theory of the mechanism of direct strokes.

### RELATION OF LINE TRIPOUT TO LIGHTNING STROKE CURRENT, TOWER FOOTING RESISTANCE AND OVERHEAD GROUND WIRES

*Wallenpaupack-Siegfried Line.* For several years efforts have been made to determine values of current in tower legs by means of the lightning stroke recorder.

In 1930, during the part of the season in which instruments were in service, records of 18 strokes were obtained, which were all interpreted as due to direct strokes. Nine of the ten strokes associated with tripout took place on the section of line not equipped with overhead ground wires; while seven of the eight strokes not associated with tripout took place on the section equipped with overhead ground wires or diverter wires.

TABLE II—LIGHTNING STROKE RECORDS—1932 FROM WALLENPAUPACK-SIEGFRIED 220-KV LINE. PRODUCT OF CURRENT X TOWER FOOTING RESISTANCE X $10^{-3}$

| | Accompanied by tripout | | | Not accompanied by tripout | | |
|---|---|---|---|---|---|---|
| Product | Number | Per cent | | Number | Per cent | |
| Less than 20 | 0 | 0 | 18.2 | 0 | 0 | 54.6 |
| 20— 100 | 2 | 18.2 | | 12 | 54.6 | |
| 100— 200 | 1 | 9.1 | 36.4 | 4 | 18.2 | 36.3 |
| 200— 300 | 1 | 9.1 | | 2 | 9.1 | |
| 300— 500 | 0 | 0 | | 1 | 4.5 | |
| 500—1,000 | 2 | 18.2 | | 1 | 4.5 | |
| 1,000—2,000 | 0 | 0 | 45.4 | 2 | 9.1 | 9.1 |
| 2,000—5,000 | 3 | 27.2 | | 0 | 0 | |
| Over 5,000 | 2 | 18.2 | | 0 | 0 | |
| | 11 | 100.0 | | 22 | 100.0 | |

Range of
Product—48 to 9,870
Current—4,000 to 180,000 amp

Range of
Product—24 to 1,175
Current—2,000 to 25,000 amp

In 1931 records were obtained of 53 strokes. Of these, 19 were accompanied by tripout and 34 were not accompanied by tripout.

In Table I are listed for these 53 strokes the product of tower current times tower footing resistance times $10^{-3}$, the product being proportional to kilovolts. The values used for resistance are the measured values for tower footings, with tower footing grounding cables or counterpoises, but without taking into account the effect of overhead ground wires.

In 1932, records were obtained of 33 strokes, of which 11 were accompanied by tripout and 22 not accompanied by tripout. In Table II are listed the product of tower current times tower footing resistance times $10^{-3}$ for the year 1932.

The records are usually grouped in several adjacent towers, all probably due to one stroke. In each group there is usually one high current reading and a number of smaller ones. In these tables are included only the maximum product for each group, as it is probable that this is the product which is of importance in connection with flashover.

It will be noted from these tables that a much greater percentage of the products are high for the records accompanied by tripout than for those not accompanied by tripout.

In Table III are summarized the lightning stroke recorder records for the three years, with particular reference to their location with respect to overhead ground wires.

It will be noted from this table that under the heading *Accompanied by Tripout,* from 80 to 100 per cent of the records were obtained on the section without overhead ground wires. The total number of records in the section without overhead ground wires varied from 52 to 68 per cent of the total for the whole line, which corresponds, roughly, with the length of the section without overhead ground wires, which is 57 per cent of the total length.

In other words, although the strokes were fairly well distributed over the whole line, the strokes causing tripout were concentrated on the section without overhead ground wires.

The data secured during these three years show conclusively the beneficial effect of overhead ground wires in preventing flashover and tripout.

On the section of the Wallenpaupack-Siegfried line equipped with overhead ground wires and counterpoise, tower WT-11-4 to tower WT-14-1 (14 towers in all), the flashed insulator assemblies for the years 1926 to 1932 were as follows (the counterpoise was in service during 1929 and subsequent years):

| Year | | Flashed insulator assemblies |
|---|---|---|
| 1926 | No overhead ground wires | 6 |
| 1927 | Ground wires installed | 9 |
| 1928 | Ground wires in service | 14 |
| 1929 | Counterpoise installed | 0 |
| 1930 | Ground wires and counterpoise in service | 0 |
| 1931 | Ground wires and counterpoise in service | 0 |
| 1932 | Ground wires and counterpoise in service | 0 |

It is apparent that to be really effective the ground wires must be supplemented by low tower footing resistance.

*Philo-Canton Line.* In 1931, records were obtained with the lightning stroke recorder of 25 strokes, involving 1 to 13 towers in each stroke. The tower current values varied from 2,000 to 80,000 amperes. All of the readings were negative, except those discussed in the following paragraph.

On June 26th, a chestnut tree, located 150 ft west of mid-span, between towers 174 and 175, was struck. Currents of 6,000 amperes positive were recorded at both towers 174 and 175. There was no indication of flashover and no tripout.

There were 7 tripouts on this line, of which 4 were due to flashover in the area covered by lightning stroke recorders (about 22 miles out of 73 miles total). Records were obtained of tower current in each of the four cases. The product of tower current times tower footing resistance gave values of indicated voltage much lower than the assigned flashover values in these four cases. The suggestion has been made that direct stroke to the conductor took place in these cases (it will be remembered that this is a double circuit line with one ground wire).

TABLE III—SUMMARY OF LIGHTNING STROKE RECORDER RECORDS WALLENPAUPACK-SIEGFRIED 220-KV LINE

| | 1930 | | 1931 | | 1932 | |
|---|---|---|---|---|---|---|
| | Ground wires | No ground wires | Ground wires | No ground wires | Ground wires | No ground wires |
| Accompanied by tripout | 1 | 9 | 0 | 19 | 2 | 9 |
| Not accompanied by tripout | 7 | 1 | 17 | 17 | 14 | 8 |
| | 8 | 10 | 17 | 36 | 16 | 17 |

Assuming that tower currents of 10,000 amperes or more were due to direct strokes, then 15 of the 25 groups of records would be classed as direct strokes and the remaining 10 may have been produced by direct or induced strokes.

Of the 15 groups of records classed as direct strokes, 4 correlated with line tripout. The remaining 11 groups were not accompanied by line tripout.

Of the 7 tripouts experienced in 1931, 5 involved both circuits of the double-circuit line and 2 involved only 1 circuit.

In 1932, records were obtained with the lightning stroke recorder of nine strokes, involving 2 to 12 towers in each stroke. Maximum tower current values varied from 3,500 to 20,000 amperes. All strokes were negative.

*Deepwater-Pleasantville Line.* In 1931, readings were obtained with the lightning stroke recorder in the case of 5 strokes, involving from 1 to 6 towers per stroke. Maximum tower currents varied from 2,000 to 113,000 amperes. All readings were negative.

There were 6 tripouts, of which only 1 correlated with lightning stroke recorder readings (in the other cases there were no lightning stroke recorders near the point of flashover). In the case which correlated (stroke No. 2) there was a reading of 113,000 amperes at tower 70, and small readings up to 7,000 amperes in 5 adjacent towers. The product of current times tower footing resistance times $10^{-3}$ at tower 70 was about 4,000 kv. Surge indicators operated on all three phases of circuit 2 at tower 70. Circuit 2 tripped out at both ends.

Two of the 6 tripouts involved both circuits and 4 involved only 1 circuit.

In 1932, only 2 strokes were recorded by the lightning stroke recorder. These involved 2 and 4 towers, respectively. Maximum tower currents recorded were 3,500 and 4,500 amperes. Both strokes were negative.

*Glenlyn-Roanoke Line.* Only one year's records are available on this line.

In 1932, eight readings were obtained with the lightning stroke recorder, involving from 2 to 4 towers per stroke. Maximum tower currents varied from 1,000 to 108,000 amperes. All strokes were negative.

## PROTECTION OF TRANSMISSION LINES BY OVERHEAD GROUND WIRES

*Induced Strokes.* Protection from induced strokes is best accomplished by means of overhead ground wires. Two ground wires placed directly above the conductors in vertical configuration or placed above and between the conductors in horizontal arrangement are usually sufficient for all practical purposes. The ground wires are placed above the conductors, a distance of 10 to 20 ft in the average case. Such an arrangement will reduce the induced voltage 50 to 70 per cent.[5]

The material of the ground wire is not important from the lightning standpoint, but for other reasons high conductivity ground wires are preferable. Tower footing resistances up to 75 or 100 ohms are tolerable.

*Direct Strokes.* For direct strokes, theoretical analysis indicates that the ground wires should be placed so that the conductors to be protected fall within a triangle formed by the ground wire as the apex and a base line on the ground equal to two or three times the height of the ground wire above ground. It is also required that the distance between the ground wire and conductors at mid-span is sufficient to withstand the full potential built up between them until this potential has had a chance to be relieved by waves traveling from the point of contact of the stroke to the ground via the towers. Such considerations call for ground wires 30 to 50 ft above the conductors.[5,6]

In practise, it has been found that conventional ground wires (placed as for induced strokes—10 to 25 ft above the conductors) will prevent flashover of the transmission line insulation, providing the insulation is reasonably strong and providing the resistance between the top of tower and ground is low. The larger part of this resistance is in the tower footing itself.

If the line insulation flashes over due to lightning, there may be no tripout, provided the ratio of the 60-cycle flashover of the line insulation to the circuit voltage is sufficiently high.

The following table gives the number of insulator units and tower footing resistances of steel tower lines with overhead ground wires, which are believed to be of the proper order to prevent lightning flashover, due to tower current, or follow-up of normal frequency current, except possibly in case of unusually severe direct strokes. Very little data on this subject have been accumulated in practise, so that the figures in the table should be regarded as quite tentative:

| Circuit voltage | Insulation to prevent normal frequency follow current (units)* | Maximum tower footing resistance to prevent lightning flashover (ohms)† |
|---|---|---|
| 66 | 8 | 6 |
| 132 | 12 | 8 |
| 220 | 20 | 12 |

*Based on 10-inch disks with 5¾-inch spacing.

†Based on 200,000 amperes in tower.

In the United States and Canada at the present time, there are approximately 2,000 miles of 220-kv line with insulation varying from 12 disks to 18 disks (spaced 5¾ inches, or equivalent). Only one of these lines has been immune from flashover and interruption. However, the interruptions in many cases have been as low as one to three per 100 miles per year.

### IMPORTANCE OF DIRECT AND INDUCED STROKES

The question of relative importance of direct and induced strokes, particularly on the lower voltage lines, is still unsettled. Opinion has drifted toward the direct stroke standpoint. The only direct evidence obtained by measurement is the mass of data secured with the lightning stroke recorder. The larger currents indicated can only be explained on the basis of direct strokes.

However, there have been small currents indicated which might be caused by induced strokes. Strokes to trees and simultaneous voltages recorded on transmission lines also indicate induced surges (see record of stroke on the Ohio Power Company's system, discussed in this paper, and records of several strokes on the Ohio Power and Louisiana Power and Light Companies systems, discussed in the authors' 1931 paper).[1]

### POLARITY OF LIGHTNING STROKES

The additional data which have been obtained on direct stroke currents continue to show that polarity is of dominant importance in the lightning stroke mechanism. Table IV summarizes lightning stroke measurements of transmission line tower leg currents to date, classifying them as to relative current range and polarity and giving the number of line tripouts with each group. These data are from records obtained on the Pennsylvania-New Jersey 220-kv interconnection, Philo-Canton line, and Deepwater-Pleasantville line. In this table only the maximum current of each group of records is included. The accuracy of current values given in this table are somewhat uncertain. The authors feel, however, that no doubt exists as to the polarity classification and that the relative order of current magnitude is sufficiently correct, except where noted, to justify the analysis given.

TABLE IV—LIGHTNING STROKE CURRENT MEASUREMENTS IN TOWER LEGS

| Current range amperes* | | Positive strokes | Correlated tripouts | Negative strokes | Correlated tripouts |
|---|---|---|---|---|---|
| 1,000 | 2,000 | 0 | 0 | 25 | 2 |
| 2,000 | 3,000 | 0 | 0 | 13 | 1 |
| 3,000 | 4,000 | 3 | 1 | 12 | 1 |
| 4,000 | 5,000 | 17 | 0 | 8 | 0 |
| 5,000 | 6,000 | 7 | 0 | 4 | 1 |
| 6,000 | 7,000 | 1 | 1 | 1 | 0 |
| 7,000 | 8,000 | 0 | 0 | 6 | 1 |
| 8,000 | 10,000 | 2 | 1 | 7 | 0 |
| 10,000 | 15,000 | 0 | 0 | 9 | 4 |
| 15,000 | 25,000 | 2 | 1 | 9 | 3 |
| 25,000 | 40,000 | 1 | 1 | 7 | 5 |
| 40,000 | 60,000 | 0 | 0 | 18 | 7 |
| 60,000 | 80,000 | 0 | 0 | 13 | 6 |
| 80,000 | 100,000 | 0 | 0 | 9 | 4 |
| 100,000 | 150,000 | 0 | 0 | 19 | 8 |
| 150,000 | 200,000† | 1 | 0 | 5 | 1 |
| 200,000 | 300,000† | 0 | 0 | 12 | 2 |

*These values are subject to modification on account of uncertain instrument calibration.

†These high current values were obtained with an early recorder arrangement which it is believed gave excessive values.

It is to be noted that the table shows a great number of small negative currents in the range 1,000 to 5,000 amperes, an intermediate group of positive currents, ranging from 3,000 to 6,000 amperes, and a group of high negative currents, ranging from 10,000 to 150,000 and centering about 80,000 amperes.

*Tripouts Occur With the High Negative Currents Almost Exclusively.* This important fact must receive careful attention. Data published by several authors[7,8] indicate that positive cloud-to-ground strokes do take place frequently, probably more frequently than negative cloud-to-ground strokes. However, the data of Table IV show negative strokes to the line to predominate in number and in current magnitude.

The authors of this paper have previously called attention[2] to the influence of electrode shape in relation to polarity in the case of flashover between dissimilar electrodes under atmospheric conditions. The following quotation[9] describes the point very clearly: "Investigation shows that it is the form and intensity of the dielectric field at, or near, the positive terminal which has the greatest effect on the disruptive voltage of the air gap; while the field at, and near, the negative terminal is of secondary importance. Thus, if at constant gap length the positive terminal is gradually changed in steps from a sharp point to a flat plate, while the negative terminal remains unchanged in form, the disruptive voltage changes correspondingly over a wide range. A corresponding change in the physical form of the negative terminal, however, with the positive terminal unchanged in form, varies the disruptive voltage relatively little." In terms of voltage values which are familiar in every day laboratory work, this phenomenon may be stated somewhat as follows:

For dissimilar electrodes, such as point-plane, the breakdown voltage for point positive is one-third or one-fourth that for point negative. As far as laboratory phenomena are concerned, this viewpoint is generally agreed upon. In connection with natural lightning, however, various opinions are held regarding the significance of this electrode shape-polarity effect. It is believed by the authors that the polarity characteristics of available lightning stroke current data strongly indicate the importance of this effect.

The cloud may be considered as a non-conducting electrode of relatively smoothly rounded contours. The earth is a conducting plane from which, in most cases, protrudes rather sharp points, such as trees, steeples, and transmission line towers. Now, it follows very reasonably from laboratory experience, such as described above, that when a conducting projection from the earth is positive in polarity, relative to the cloud, and the cloud potential is sufficiently high, the projection will form a terminal for discharge between the two. Also, the entire current associated with the cloud discharge must pass through this projection, because its presence has initiated the discharge. Furthermore, the negative polarity of the relatively smooth cloud is not at all suitable for the formation of breakdown streamers at the cloud. Accordingly, cloud potential will increase until a suitable projection from the conducting earth provides a high gradient point at the positive terminal. The conditions for minimum breakdown potential under this polarity arrangment are met and the discharge proceeds. This lightning stroke is, it is believed, progressing into a uniform or converging field, a single breakdown channel through which the entire current associated with a negative polarity cloud passes. In laboratory experiments this directive effect of the positive point has been shown to protect an adjacent area of radius of 15 times the projection height.

Where the cloud is positive and the earth negative, projections on the earth's surface have little directive effect.[2] Here it appears that breakdown streamers from the positively charged cloud,[10] originating at the cloud, proceed with considerable branching toward the seat of the induced charge. The positive polarity of the cloud is suitable for streamer formation, and the usually diverging cloud field gives rise to branching. Under these conditions, laboratory tests have shown a protected area adjacent to a projection of radius equal to two or three times the projection height. A standpoint, such as that described above, is well in accord with the data of Table IV. The high negative cloud discharge currents, severe in that they practically alone cause line tripouts, reach the line structure frequently because of its directive effect as a positive polarity projection above the conducting plane of the earth. Positive cloud-to-ground strokes reach the line less frequently, as again shown by the table, and then are within the intermediate current range 3,000 to 6,000 amperes and do not often cause tripouts. It is agreed, of course, that with sufficiently high tower footing resistances, currents of this range would produce flashover. The positive strokes to ground do not reach the line in greater numbers in spite of their frequency, because of the lack of directive effect of the line charged negatively. Also, such strokes when they do chance to strike the line are less severe because of extensive streamer branching, which exhausts the cloud energy and gives lower tower currents. The large group of low current records are believed not to be due to direct strokes, but of induced origin. These records are principally of negative polarity, as should be the case if induced by nearby positive cloud-to-ground strokes. Such nearby positive strokes are in accord with the above analysis.

To maintain the correct standpoint regarding the mechanism of cloud discharge, it must always be kept in mind that the cloud potentials are building up relatively slowly. The lightning flash awaits a breakdown gradient at some point in the cloud field. Thus, the field configuration, depending upon cloud and ground conditions and polarity, are critical. When these are lost sight of in consideration of uniform fields and plane electrodes, the true elements of the picture are lost. For instance, it is generally agreed that in certain localities lightning storms are frequent, but transmission line service interruptions are rare. When this is considered in the light of the polarity effects described above, possible explanations are readily forthcoming. The relative positions of the positive and negative cloud charges and their distances to ground are important. Difference of opinion exists regarding the normal distribution of charge, whether the two polarities are on the same level or one is above the other is somewhat uncertain. One series of data[7] indicates strongly that the positive charge is below and the negative above. Another very thorough study[8] of the mechanism of accumulation of cloud charges reverses this relative position. Probably the atmospheric conditions changing greatly with geographical location and season make for considerable variation in charge position. At this time, it is sufficient to note that an elevation of the negative charge position of the cloud relative to ground without change in positive charge location would probably eliminate many of the severe negative strokes without affecting greatly the number of positive cloud-to-ground strokes, or causing a noticeable reduction in lightning severity from the casual observer's point of view. Of course, an elevation of the entire cloud would decrease the cloud-to-ground and increase the cloud-to-cloud strokes.

## LABORATORY LIGHTNING TESTS

Many instances, wherein attempts have been made in the laboratory to demonstrate the mechanism of natural lightning have led to uncertain conclusions. Some observers doubt the value of such tests entirely, while others see in almost every laboratory discharge some aspect of natural lightning. Somewhere between these two must lie the most valuable standpoint. Many laboratory observers have made helpful contributions and further experimentation is very desirable. Several factors, however, should be kept in mind when laboratory studies of the mechanism of natural lightning are being conducted, so that uncertainties will be eliminated. Field conditions should be simulated as closely as possible. For instance, a study of conditions surrounding the precipitation of the stroke should utilize as close a representation as possible of natural conditions. It is not difficult to show that branching streamers may be directed away from a negative electrode if suitable electrode arrangements are utilized, but such a test does not justify the viewpoint that branching away from a negatively charged cloud occurs in thunderstorms.[11] Also, since impulse testing of insulators has become common, observers have endeavored to interpret some of the results obtained in this field as indicative of aspects of the mechanism of natural lightning. It is not believed that this will prove to be a helpful practise. The slowly increasing voltage of the cloud is not simulated by the rapid surge of the impulse. Particularly, time lag effects enter into the impulse testing results in entirely different ways than are obtained in direct-current testing. Careful laboratory experiments[12] have shown that the point-plane effect, which has now been shown to dominate the natural lightning picture, grows less pronounced as the time duration of the impulse decreases. Again, in impulse testing overvoltages are always applied and in natural lightning only the lowest flashover voltage is obtained with continuous potential. Of course, the field for such investigations is wide and only careful attention to such details will produce good results.

### CONCLUSIONS

The overhead ground wire is definitely shown to be effective in reducing line tripouts.

The beneficial effects of low tower footing resistance are apparent from the data and analysis.

The counterpoise is shown to be effective in securing low tower footing resistance.

Line insulation and permissible tower footing resistance specifications, which will render the lines practically immune from flashover, may be written.

For a good understanding of how direct strokes which cause tripout chance to terminate on the transmission line and reach current values sufficient to give insulator flashover, it is necessary to consider polarity characteristics of the cloud and of flashover between dissimilar electrodes.

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## Discussion

**A. E. Davison:** Engineers usually are so busy protecting those transmission lines and works which are very much exposed to weather hazards, more particularly lightning, that they neglect to call in the physicist. Some engineers even go so far as to advocate lightning proof designs and terminal equipment. Are these attempts to secure lightning proof lines always the most economical methods by which the continuity of services can be attained?

There is considerable evidence according to Dauzere, who addresses the International High Tension Conference and other French technical and physical organizations, that the incidence of lightning is not as uniformly spread over large areas as a layman would expect for such an extremely fortuitous natural phenomenon as lightning. He pictures electrical pockets in the lower atmosphere through which lightning discharges may be expected to be more frequent. As compared with his suggestions, one would naturally expect that variations in elevation of terrain should affect the discharging of storm clouds moving across an area and that the sides of escarpments and mountains would be marked extensively by lightning discharges and would be frequently burned over. This assumption is not always borne out by observations.

Turning to the protection of rural buildings against lightning, some of us can recall a considerable relief upon having rodded a transmission line or a set of buildings, electrically. The lightning does not seem to strike as often. Is this some pyschological conclusion or is it a fact? Do these lightning rods drain off the effectiveness of a discharge between earth and clouds to the extent that there frequently is no sudden dynamic or electrical display as storm clouds pass? Many engineers know of quite local areas where strokes are relatively frequent. Transmission men, especially, know of lines or sections of lines which they would, after the fact, like to re-route on account of lightning outages. The objectionable locations may, for instance, be on the sides of hills or mountains and in other cases in comparatively flat areas. Why?

This discussion is submitted in order to suggest that utility engineers might very well ask a physicist, or men who are qualified to study geophysical conditions to look into the terrain more fully. It may be that engineers will thereby be directed when projecting their longer lines to go around an area. This would alter the apparent economies by 2 to 5 per cent due to an increased length of line, but would avoid districts recognized by geophysical examinations and analyses to be subject to lightning. They might be directed to place a line on areas recognized to be comparatively free from lightning effects.

If lightning is responsible for by far the largest group of interruptions to services, then it is desirable that we should study the phenomenon more fundamentally rather than give attention exclusively to the practise of trying to design relatively expensive transmission lines and connected apparatus sometimes referred to as lightning proof.

**I. W. Gross:** Theory and practise must go along together, if a firm foundation is to be laid for our knowledge of lightning, and the application of effective protective measures to lines and apparatus. Considering the factors still unknown in the mechanism of a lightning stroke itself, and its effect on a transmission line, it is clear that theory alone may lead to erroneous and impracticable conclusions if not checked by actual experience. On the other hand, actual operating experience alone may lead one astray, if results are not carefully analyzed and coordinated with theory. Certainly, slower progress will be made if we do not check over experience with theory continually.

That direct strokes to a transmission line can take place, in many cases without line tripout, is a statement which would hardly be made some six years ago. However, the data in this paper prove this actually does take place.

The beneficial effect of lowering the tower footing resistances to prevent line flashover has been predicted by theory, stated by general considerations, and definitely proved by experience, as given by the summarized data in this paper and that of Mr. Sporn, see page 482 of this issue.

The statement is made by the authors that "Tower footing resistances up to 75 or 100 ohms are tolerable". Does this apply only to direct strokes? Certainly, this is not true if the line outages due to lightning, irrespective of the origin of the lightning, are to be reduced to a reasonable number. In Mr. Sporn's paper it is shown that, on the average for ten different lines, increasing the average tower footing resistance from 5 ohms to 20 ohms increased the line outages 100 per cent. At the particular towers where flashover occurred on 5 lines, about 75 per cent of the flashovers occurred at towers having a footing resistance less than 75 ohms, and over 20 per cent of the flashovers at towers having a footing resistance less than 5 ohms. Tower footing resistances considerably lower than have been talked of in the past, appear to be necessary to make a line immune to lightning flashover.

At the top of page 478 is given a table of the number of insulators, required for different voltage lines, which are referred to as being of the proper order to prevent follow-up of normal frequency current. The experience on the lines of the American Gas and Electric Company indicates that the insulation suggested is too low. In fact we have almost come to the conclusion, based on recent experience, that it is practically impossible to overinsulate a line, within practical limits, so that it will be immune to 60-cycle follow-up current.

Table I shows a two-year record of four lines operated in the 33- to 66-kv voltage range. In the case of the Muncie-Anderson 33-kv line, with 132-kv insulation (10-5-1/8 in. units) the outages on a 100-mile per year basis were 10.8 against a system average on some 1,500 miles of 132-kv line, of 16.7 outages. This overinsulation certainly does not look promising, as a means of preventing 60-cycle follow-up current on low voltage lines, even with tower footing resistances as low as 5 ohms, which was the case with the Muncie-Anderson 33-kv line.

**W. W. Lewis and C. M. Foust:** The statement referred to by Mr. Gross, namely, that "Tower footing resistances up to 75 or 100 ohms are tolerable," refers only to induced strokes. Under the heading "Direct Strokes" tower footing resistances not over 6 to 12 ohms are recommended.

TABLE I—LIGHTNING OUTAGES ON OVER INSULATED LINES—1930-1931

American Gas and Electric Company Steel Tower Lines

| Line | Circuits | Ground wires | Tower footing resistance | Operating kv | Insulators and spacing | Outages/100 miles of line per year |
|---|---|---|---|---|---|---|
| 1. Deepwater-Pleasantville | 2 | 2 | 45.5 | 66 | 10–4–3/4 | 12.3 |
| 2. Beaver Creek-Hazard | 1 | 1 | | 44 | 10–5–1/8 | 19.4 |
| 3. Muncie-Anderson | 2 | 1 | 5.0 | 33 | 10–5–1/8 | 10.8 |
| 4. South Point-Portsmouth | 2 | 1 | | 33 | 10–5–1/8 | 24.0* |
| 5. 132-kv system 2-year average (1930-31) | | | | | | 16.7 |
| 6. 66-kv line—less outages due to flashover at graded insulators | | | | | | 7.9 |
| 7. 44- and 33-kv lines—less outages due to flashover at graded insulators | | | | | | 13.6 |

*1931 record only.

# Lightning Experience on 132-Kv Transmission Lines of the American Gas and Electric Company System

## 1930-1931

BY PHILIP SPORN*

Fellow, A.I.E.E.

*Synopsis—This paper, which is a continuation of a four-year operating record of an extensive 132-kv transmission system under lightning conditions, presents and discusses the record for 1930 and 1931.*

*Operating experience is given on:*

*1. Yearly line outages due to lightning for all lines.*

*2. Severity and frequency of lightning storms over the system for a three-year period.*

*3. Frequency of double circuit outages.*

*4. Extent of line and station apparatus damage.*

*5. Effect of tower footing resistance in reducing lightning outages.*

*6. Reduction in tower footing resistances by the use of driven ground rods and counterpoises.*

*7. Effect on lightning outages by overinsulation.*

*8. Relative frequency of single-phase, two-phase and three-phase line faults.*

*9. Location of lightning flashovers on the line in reference to top, middle and bottom conductors.*

*Conclusions are drawn from the results of the operating experience on these lines.*

### INTRODUCTION

In the final analysis, field experience, properly analyzed and interpreted, is the only safe criterion for judging performance of any engineering structure, piece of equipment, or system embodying them. This holds true particularly for transmission lines where a great deal of time must of necessity elapse before it can definitely be determined whether or not satisfactory results have been obtained from new designs, design changes, or remedial measures adopted. It is the purpose of this paper to give such an analysis of a large 132-kv transmission system, where an attempt at keeping accurate and careful records of lightning performance has been made, and, in so far as possible, interpret these records and their bearing on the various phases of the lightning protection problem.

### DESCRIPTION OF SYSTEM INVESTIGATED

The system investigated comprises, at the present time, some 1,450 miles of right-of-way, including approximately 850 miles of double-circuit line, 600 miles of single-circuit line, and a total of 2,200 miles of three-phase circuit. The general extent of the system and territory covered has been previously described.[1]

Since 1929 when the last record of lightning performance on the system was reported before the Institute, the interconnected system has been increased by approximately 250 miles of right-of-way (400 miles of three-phase circuit).

Most of the transmission lines are of two-circuit steel tower[1] construction, the conductors being in vertical arrangement on each side of the tower, and in most cases at least one protective ground wire is employed. The only two wood pole lines (Logan-Sprigg and Sprigg-Beaver Creek) do not have ground wire protection. Three lines have two ground wire protection; the Twin Branch-Benton Harbor Line and the Deepwater-Pleasantville Line have one ground wire located at the peak of the tower and one directly underneath at the approximate level of the second crossarm. The Windsor-Canton Line has two ground wires, one above each circuit.

All lines are constructed with 132-kv insulation and are operated at 132 kv with four exceptions. These are the Beaver Creek-Hazard Line which is operated at 44 kv, the Deepwater-Pleasantville Line which is operated at 66 kv, and the South Point-Portsmouth and Muncie-Anderson Lines which are operated at 33 kv. It is planned eventually to cut all these lines over to 132-kv operation. Some of the details of design and construction of these different lines are listed in Table I.

The spacing of conductors on steel tower lines is in the order of 21¾ ft or more between circuits and 13 ft vertically between phase wires. The ground wire (where only one is used) is located at the tower peak approximately 10 ft above the level of the top conductors. On tower lines provided with only one ground wire, the lightning flashover between the ground wire and nearest line conductor, is in the order of 5,000 kv at suspension towers and 5,800 kv at dead-end towers. In midspan these flashover voltages are 20 to 35 per cent greater due to the difference in sag of the line and ground wires. The impulse flashover at the insulator strings (assuming an average length of string of 50 inches) is in the order of 1,250 kv. All these flashovers are on the basis of crest flashover with a ¼ by 5 microsecond impulse wave.

The type of country through which these lines extend varies from flat country where the tower footing resistances are in the order of 2½ ohms, such as in Indiana, to very hilly mountainous country where footing resistances reach magnitudes of 200 ohms and over.

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[1] For references see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., Jan. 23-27, 1933.*

### PROTECTIVE EQUIPMENT

The general type of lightning protective equipment supplied on the 132-kv system consists of lightning arresters at all major substations, graded insulation at station entrances, the use of ground wires on most lines (see above), and in a few cases the installation of ground rods and/or counterpoises at the base of the line towers. Additional ground rods were installed on the Twin Branch-Benton Harbor Line before it was placed in service and on the Deepwater-Pleasantville Line after it had been placed in service. Counterpoises, that is, buried conductors, have been installed on parts of the Deepwater-Pleasantville and Glenlyn-Roanoke Lines since they have been placed in service. The counterpoises were installed on the Deepwater-Pleasantville Line in the summer of 1931 and on the Glenlyn-Roanoke Line in the summer of 1932.

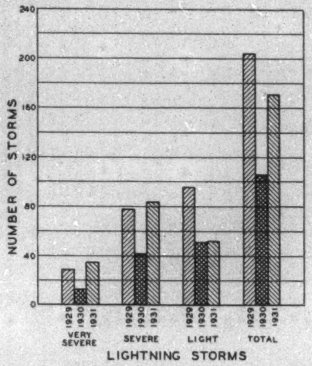

Fig. 1—Lightning Storm Severity, 1929-1930-1931

Deepwater
Fostoria
Roanoke
Reusens
Atlantic City
Glenlyn
Canton
Turner
Lima
Philo
Logan

Total storms reported by operators at above stations

Graded insulation at station entrances consists of reducing insulation on from one tower to a half mile back from the station, by one or more insulator units below the standard suspension string. This, in general, leaves the lightning flashover at the station limited to the flashover of from eight to nine standard insulator units provided with grading shields.

### OPERATING PERFORMANCE

*Line Outages.* The detailed operating performance of the 31 lines is given in Table I. The number of outages in 1928 to 1931 inclusive is summarized in Table II. It will be noted that the number of outages on a unit basis is considerably greater in 1929 and 1931 than in 1928 and 1930. The reason for this may be attributed to the more severe lightning seasons in 1929 and 1931 than in the other two years. Data bearing out this statement are shown graphically in Fig. 1.

This record has been compiled from the reports of operators located at the various substations over the system; it shows not only a greater number of storms in 1929 and 1931 but also an increased severity during those two years. The contrast between 1929 and 1930 in each of the three classes of storms (very severe, severe, and light) for which data are given is particularly striking, and again shows the necessity for some accurate measure of lightning severity if proper comparisons are to be made of line performance from year to year.

Of the three years for which lightning storm records are available, 1929 apparently shows up as the worst; and the outage record given in Table II is worse in 1929 than in any other of the four years shown.

TABLE II—AVERAGE LINE OUTAGES PER 100 MILES OF LINE PER YEAR

| | 1928 | 1929 | 1930 | 1931 |
|---|---|---|---|---|
| All lines | 13.5 | 21.6 | 13.7 | 19.8 |
| Two-circuit lines | 17.7 | 23.3 | 12.5 | 15.9 |
| One-circuit lines | 10.0 | 17.8 | 15.2 | 25.1 |
| Lines insulated for 132 kv but operating at 66 kv | | | 14.1 | 10.5 |
| Lines insulated for 132 kv but operating at 66 kv, less outages at graded sections | | | 10.5 | 5.3 |
| Lines insulated for 132 kv but operating at 33 and 44 kv | | | 13.4 | 19.2 |
| Lines insulated for 132 kv but operating at 33 and 44 kv, less outages at graded sections | | | 13.4 | 11.8 |

Another point of interest brought out in Table II is the record of lines insulated for 132-kv but operated at a lower voltage. These lines on 33-, 44- and 66-kv operation show, it is true, a smaller number of outages than lines similarly insulated but operated at 132-kv. This is particularly so if the records are compared on the basis of omitting those outages which have been charged to flashovers on the graded insulation sections of the line. But even under those conditions, the reduction is not at all in line with what one might expect from the large reduction in operating voltage. It would appear, therefore, that it is not a practicable matter to so over-insulate a line that it will be immune to the follow-up current in the case of lightning flashover, even when the operating voltage is as low as 33-kv and the ratio of insulation employed is 4:1 of that normally used.

### DOUBLE-CIRCUIT LINE OUTAGES

In previous records[1] it has been shown that, on two circuit lines, in only 15 to 29 per cent of the cases of outage did both lines trip. In 1931, however, the percentage of outages where both lines tripped out during lightning disturbances rose to 40 per cent. This record is shown graphically in Fig. 2. While the outages per 100 miles of line per year have, in general,

### TABLE I—LIGHTNING RECORD 132-KV LINES OF AMERICAN GAS AND ELECTRIC COMPANY

1929-30-31

| 1 | | 2 Beaver Creek Hazard | 3 Deepwater Pleasant ville | 4 Ft. Wayne Marion Muncie | 5 Glenlyn Roanoke | 6 Glenlyn Switch-back | 7 Howard Ashland | 8 Howard Fostoria | 9 Lima Ft. Wayne | 10 Lima Fostoria | 11 Logan[1] Sprigg | 12 Marion Kokomo | 13 Muncie Anderson | 14 Philo Canton | 15 Philo Zanes. Ckavl. | 16 Philo S.P. Turner |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length of line | Miles | 28.4 | 56.9 | 80.6 | 65.0 | 30.0 | 20.9 | 44.9 | 63.2 | 45.6 | 21.0 | 28.9 | 18.5 | 73.0 | 15.4[2] | 167.2 |
| Insulators/suspension string | No.-space | 10–5–1/8 | 10–4–3/4 | 10–5–1/8 | 11–4–3/4[3] | 11–5–1/8[3] | 10–5–1/8 | 10–5–1/8 | 9–5–3/4 | 12–4–3/4[3] | 10–6–7/16 | 10–5–1/8 | 10–5–1/8 | 11–4–3/4[3] | 11–4–3/4[4] | 11–4–3/4 |
| Line placed in service No. 1 line | Date | 6/22/30 | 4/12/30 | 9/23/28 | 6/13/26 | 8/13/27 | 1/2/30 | 8/2/29 | 9/23/28 | 9/3/25 | 6/28/26 | 11/4/28 | 5/1/29 | 9/28/24 | 9/28/24 | 9/18/28 |
| Line placed in service No. 2 line | Date | | 4/12/30 | 10/14/28 | 6/13/26 | 8/13/27 | | | | | | 11/4/28 | | 9/28/24 | 6/11/30 | 4/22/26 |
| Ground wire placed in service | Date | 6/22/30 | 4/12/30[8] | 9/23/28 | 6/13/26 | 8/13/27 | 1/2/30 | 8/2/29 | 3/ /26 | 3/ /26 | None | 11/4/28 | 5/1/29 | 5/13/26 | 3/ /26 | 4/22/26 |
| Grading shields placed in serv. No. 1 line | Date | 6/22/30 | 4/12/30 | 9/23/28 | 5/16/28 | 8/13/27 | 1/2/30 | 8/2/29 | 5/29/26 | | | 11/4/28 | 5/1/29 | 5/13/26 | 3/ /26 | 4/22/26 |
| Grading shields placed in serv. No. 2 line | Date | | 4/12/30 | 10/14/28 | 4/30/28 | 8/13/27 | | | | | | 11/4/28 | | 5/13/26 | 6/11/30 | 6/ /30 |
| Heighth of peak std. susp. tower | Feet | 72 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 35[10] | 97 | 97 | 97 | 97 | 97 |
| Avg tower footing resistance | Ohms | | 45.5[9] | | 38.9 | | 2.2 | 2.4 | 2.5 | 2.0 | | | 5.0 | 7.8 | 5.0 | 3.7 |
| Avg towers per mile | No. | 3.74 | 5.66 | 5.68 | 4.13 | 4.26 | 5.85 | 5.70 | 4.78 | 4.70 | 7.76 | 5.69 | 5.74 | 4.07 | 4.55 | 4.10 |
| Grading shields | | *R*+*R*[11] | *R*+*R* | *R*+*R* | *R*+*R* | *R*+*H*[12] | *R*+*R* | *R*+*R* | *R*+*H* | None | None | *R*+*R* | *R*+*R* | *R*+*H* | *R*+*R*[13] | *R*+*H*[14] |
| ***1929 Lightning Performance*** | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | | | 5 | 19 | 6 | | | 0 | 4 | 16 | 1 | | 9 | 1 | 24 |
| Tripouts—both circuits | | | | 1 | 11 | 3 | | | | | | 0 | | 2 | | 3 |
| Line tripouts/100 mi of line/year | | | | 7.5 | 46 | 33.3 | | | 0 | 8.9 | 76 | 3.5 | | 15 | 6.5 | 16.3 |
| Damaged insulators (towers affected) | | | | 1.0 | 9 | 4 | | | 2 | 5 | 5 | | | 9 | 1 | 22 |
| Damaged conductors (towers affected) | | | | 1.0 | 16 | 4 | | | 0 | 0 | 6 | | | 4 | 1 | 8 |
| Arcing ring burn (towers affected) | | | | 1.0 | 27 | 13 | | | 0 | | | | | 12 | | 17 |
| Total cases of damage | | | | 1.0 | 36 | 14 | | | 2 | 5 | 7 | | | 12 | 2 | 29 |
| Cases of damage/line outage | | | | 0.17 | 1.2 | 1.6 | | | | 1.25 | 0.44 | | | 1.09 | 2.0 | 1.04 |
| Lightning storms reported/year | | | 14[15] | 61 | 52 | 60 | 36[15] | 62 | 56 | 64 | 46 | 34[15] | | 78 | 64 | 116 |
| Lightning storms/line tripout | | | | 10.1 | 1.7 | 6.7 | | | | 16 | 2.9 | 34 | | 7.0 | 64 | 4.3 |
| ***1930 Lightning Performance*** | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | 3 | 4 | 6 | 7 | 2 | 1 | 0 | 3 | 1 | 5 | 2 | 3 | 1 | 0 | 11 |
| Tripouts—both circuits | | | 4 | 3 | 4 | 3 | | | | | | 0 | 0 | 3 | 0 | 1 |
| Line tripouts/100 mi of line/year | | 10.6 | 14.1 | 11.2 | 16.9 | 16.7 | 4.8 | 0 | 4.8 | 2.2 | 23.8 | 6.7 | 16.2 | 5.5 | 0 | 10.1 |
| Damaged insulators (towers affected) | | | 1 | 0 | 7 | 4 | | | 2 | 4 | 19 | | | 4 | 1 | 5 |
| Damaged conductors (towers affected) | | | 0 | 1 | 15 | 4 | | | 1 | 1 | 12 | | | 0 | 1 | 6 |
| Arcing ring burn (towers affected) | | | 11 | 1 | 26 | 11 | | | 3 | 1 | | | | 4 | | 16 |
| Total cases of damage | | | 12 | 1 | 33 | 11 | | | 3 | 4 | 20 | | | 6 | 1 | 19 |
| Cases of damage/line outage | | | 1.5 | 0.1 | 3 | 2.2 | | | 1.0 | 4 | 4 | | | 1.5 | | 1.58 |
| Lightning storms reported/year | | 8[15] | 30 | 53 | 16 | 22 | 15[15] | 22 | 26 | 27 | 27 | 31[15] | 16[15] | 35 | 9 | 41 |
| Lightning storms/line tripout | | 5.3[16] | 3.8 | 5.9 | 1.5 | 4.4 | 30[16] | | 8.7 | 27 | 5.4 | 31[16] | 10.7[16] | 8.8 | | 3.4 |
| ***1931 Lightning Performance*** | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | 8 | 4 | 2 | 15 | 6 | 2 | 6 | 16 | 9 | 8 | 0 | 1 | 3 | 0 | 19 |
| Tripouts—both circuits | | | 2 | 0 | 15 | 2 | | | | | | 0 | 0 | 5 | 1 | 4 |
| Line tripouts/100 mi of line/year | | 28.2 | 10.5 | 2.5 | 46.1 | 26.6 | 9.6 | 13.4 | 26.3 | 19.7 | 37.1 | 0 | 5.4 | 11.0 | 6.6 | 19.4 |
| Damaged insulators (towers affected) | | 4[18] | 0 | 3 | 10 | 4 | | 2 | 4 | | | | | 6 | 1 | 2 |
| Damaged conductors (towers affected) | | 3 | 0 | 1 | 8 | 5 | | 0 | 0 | | | | | 4 | 0 | 4 |
| Arcing ring burn (towers affected) | | 0 | 6 | 4 | 21 | 12 | | 2 | 5 | | | | | 7 | 1 | 19 |
| Total cases of damage | | 5 | 6 | 4 | 23 | 13 | | 2 | 5 | | | | | 9 | 1 | 22 |
| Cases of damage/line outage | | 0.63 | 1.0 | 2.0 | 0.77 | 1.6 | | 0.33 | 0.31 | | | | | 1.13 | 1.0 | 0.96 |
| Lightning storms reported/year | | 2[15] | 27 | 45 | 32 | 23 | 11[15] | 14 | 4 | 4 | 60 | 25[15] | 17[15] | 26 | 14[19] | 76 |
| Lightning storms/line tripout | | 0.5[16] | 4.5 | 22.5 | 1.1 | 2.9 | 11[16] | 2.3 | 0.25 | 0.4 | 7.5 | | 34[16] | 4.4 | 14 | 3.0 |

[1] Wood pole line.
[2] Two-circuit line and 22.0 miles, 1930 on.
[3] One less unit on bottom conductor.
[4] When single-circuit had 12 units.
[5] Two less units on bottom conductor.
[6] Change from 10 units October 1929.
[7] 10 units before October 1929 top and middle and 9 on bottom.
[8] Two ground wires—one at peak of tower—one midway between middle phases.
[9] After ground rods were installed—before counterpoise.
[10] Height of steel crossarm.
[11] *R* & *R* equals ring and ring.

TABLE I—*Continued*—LIGHTNING RECORD 132-KV LINES OF AMERICAN GAS AND ELECTRIC COMPANY
1929-30-31

| 1 | | 17<br>Philo<br>Howard | 18<br>Roanoke<br>Roxboro | 19<br>Roanoke<br>Reusens | 20<br>Saltville<br>Kingsport | 21<br>So Bend<br>Mich.<br>City | 22<br>So. Point<br>Portsmouth | 23<br>Sprigg[1]<br>Beaver<br>Ck. | 24<br>Switchback<br>Logan | 25<br>Switchback<br>Saltville | 26<br>Turner<br>Cabin<br>Ck. | 27<br>Turner<br>Logan | 28<br>Twin<br>Branch<br>Benton Hbr. | 29<br>Twin<br>Branch<br>Ft. Wayne | 30<br>Twin<br>Branch<br>So. Bend | 31<br>Windsor<br>Canton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length of line | Miles | 80.7 | 98.3 | 43.0 | 56.0 | 40.0 | 34.5 | 39.3 | 50.0 | 38.8 | 23.6 | 40.2 | 38.0 | 65.4 | 4.9 | 55.0 |
| Insulators/suspension string | No.-space | 10–5–1/8 | 11–5–1/8[3] | 12–4–3/4[5] | 10–5–1/8 | 9–5–3/4[6] | 10–5–1/8 | 10–5–3/4 | 10–5–3/4 | 10–5–3/4 | 10–5–3/4 | 10–4–3/4 | 10–5–1/8 | 9–5–3/4 | 9–5–3/4[7] | 10–4–3/4 |
| Line placed in service No. 1 line | Date | 8/2/29 | 9/16/26 | 5/ 5/26 | 8/25/27 | 6/24/26 | 10/14/30 | 3/16/30 | 11/27/27 | 10/16/27 | 7/29/28 | 1/30/26 | 4/13/30 | 9/23/28 | 4/5/25 | 9/17 |
| Line placed in service No. 2 line | Date | | | 9/ 9/27 | | | 10/14/30 | | 11/27/27 | | 7/31/28 | 1/30/26 | 4/13/30 | | 4/ 5/25 | 9/17 |
| Ground wire placed in service | Date | 8/2/29 | 9/16/26 | 5/ 5/26 | 8/25/27 | 3/ /26 | 10/14/30 | None | 11/27/27 | 10/16/27 | 7/29/28 | 9/24/28 | 4/13/30[8] | 3/ /26 | 3/ /26 | 9/17 |
| Grading shields placed in serv. No. 1 line | Date | 8/2/29 | 9/16/26 | 5/22/26 | 8/25/27 | 6/24/26 | 10/14/30 | None | 11/27/27 | 10/16/27 | 7/29/28 | 7/20/26 | 4/13/30 | 6/ 7/26 | 6/ 8/26 | |
| Grading shields placed in serv. No. 2 line | Date | | | 9/ 9/27 | | | 10/14/30 | | 11/27/27 | | 7/29/28 | 7/20/26 | 4/13/30 | | 6/ 8/26 | |
| Heighth of peak std. susp. tower | Feet | 97 | 97 | 97 | 97 | 97 | 97 | | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 78 |
| Avg tower footing resistance | Ohms | 11.0 | | 79.1 | | | | | | | | 10.9 | 2.5 | 2.5 | | 12.0 |
| Avg towers per mile | No. | 4.93 | 4.47 | 4.65 | 4.15 | 4.59 | 4.43 | 5.52 | 3.78 | 4.50 | 4.23 | 3.36 | 5.49 | 4.61 | 4.9 | 8.84 |
| Grading shields | | *R+R* | *R+R* | *R+H* | *R+H* | *R+H* | *R+R* | None | *R+H* | *R+H* | *R+R* | *R+H* | *R+R* | *R+H* | *R+H* | None |
| *1929 Lightning Performance* | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | | 32 | 11 | 13 | 9 | | | 11 | 16 | 4 | 11 | | 7 | 1 | 2 |
| Tripouts—both circuits | | | | 5 | | | | | 9 | | 3 | 4 | | | 2 | 0 |
| Line tripouts/100 mi of line/year | | | 32.5 | 37.2 | 23.2 | 22.5 | | | 40 | 84.8 | 29.6 | 37.4 | | 10.7 | 61.2 | 3.6 |
| Damaged insulators (towers affected) | | | 5 | 4 | 1 | 3 | | | 10 | 5 | 6 | 3 | | 5 | 2 | 0 |
| Damaged conductors (towers affected) | | | 15 | 5 | 5 | 3 | | | 6 | 4 | 3 | 3 | | 4 | 2 | 1 |
| Arcing ring burn (towers affected) | | | 32 | 16 | 17 | 0 | | | 17 | 16 | 12 | 16 | | 0 | 0 | |
| Total cases of damage | | | 34 | 18 | 17 | 3 | | | 20 | 17 | 12 | 17 | | 8 | 3 | 1 |
| Cases of damage/line outage | | | 1.1 | 1.1 | 1.3 | 0.33 | | | 1.0 | 1.06 | 1.71 | 1.13 | | 1.15 | 1.0 | 0.50 |
| Lightning storms reported/year | | | 31[15] | 48 | 41 | 33[15] | | | 69 | 56 | 77 | 83 | | 20 | 35 | 63 |
| Lightning storms/line tripout | | | 2.0[16] | 3.0 | 3.2 | 7.3[16] | | | 3.5 | 35 | 11 | 5.5 | | 3.0 | 11.7 | 31.5 |
| *1930 Lightning Performance* | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | 3 | 46 | 8 | 7 | 1 | | 11 | 7 | 9 | 1 | 4 | 3[17] | 3 | 1 | 0 |
| Tripouts—both circuits | | | | 3 | | | | | 1 | | 2 | 1 | 0 | | 0 | 0 |
| Line tripouts/100 mi of line/year | | 3.7 | 46.7 | 25.6 | 12.5 | 2.5 | 0 | 28 | 16 | 23.2 | 12.7 | 12.5 | 7.9 | 4.6 | 20.4 | 0 |
| Damaged insulators (towers affected) | | 2 | 12 | 8 | 1 | | | 1 | 5 | 6 | 1 | 3 | | | | 0 |
| Damaged conductors (towers affected) | | 0 | 19 | 10 | 7 | | | 3 | 2 | 11 | 2 | 4 | | | | 0 |
| Arcing ring burn (towers affected) | | 5 | 39 | 20 | 7 | | | | 9 | 14 | 4 | 17 | | | | 0 |
| Total cases of damage | | 5 | 51 | 26 | 8 | | | 3 | 10 | 16 | 4 | 20 | | | | 0 |
| Cases of damage/line outage | | 1.67 | 1.1 | 2.3 | 1.1 | | | | 1.25 | 1.78 | 1.33 | 4.0 | | | | 0 |
| Lightning storms reported/year | | 20 | 8[15] | 15 | 17 | 15[15] | 18[15] | 8[15] | 33 | 27 | 27 | 37 | 0 | 6[15] | 15 | 20 |
| Lightning storms/line tripout | | 6.7 | 0.3[16] | 1.4 | 2.4 | 30[16] | | 1.5[16] | 4.1 | 3.0 | 9.0 | 7.4 | | 4.0 | 15[16] | |
| *1931 Lightning Performance* | | | | | | | | | | | | | | | | |
| Tripouts—one circuit only | | 5 | 36 | 15 | 9 | 6 | 4 | 17 | 10 | 21 | 3 | 5 | 0 | 10 | 0 | 0 |
| Tripouts—both circuits | | | | 11 | | | 5 | | 7 | | 1 | 5 | 4 | | 0 | 2 |
| Line tripouts/100 mi of line/year | | 6.2 | 36.6 | 60.5 | 16.1 | 15 | 26.1 | 43.2 | 34 | 90.5 | 17 | 24.8 | 10.5 | 15.3 | 0 | 3.6 |
| Damaged insulators (towers affected) | | 1 | 3 | 4 | 3 | 6 | 11 | 3 | 11 | 5 | 7 | 3 | 5 | 2 | | 2 |
| Damaged conductors (towers affected) | | 0 | 5 | 2 | 2 | 2 | 7 | 5 | 7 | 9 | 2 | 4 | 1 | 0 | | 2 |
| Arcing ring burn (towers affected) | | 5 | 17 | 23 | 16 | 4 | 4 | | 26 | 28 | 9 | 10 | 4 | 1 | | |
| Total cases of damage | | 5 | 18 | 25 | 16 | 6 | 15 | 6 | 28 | 28 | 10 | 11 | 5 | 3 | | 2 |
| Cases of damage/line outage | | 1.0 | 0.5 | 0.96 | 1.6 | 1.0 | 1.67 | 0.35 | 1.65 | 1.33 | 2.5 | 1.1 | 1.25 | 0.3 | | 1.0 |
| Lightning storms reported/year | | 21 | 17[15] | 24 | 34 | 24[15] | 25[15] | 35 | 35 | 31 | 48 | 68 | 0[15] | 3 | 24 | 26 |
| Lightning storms/line tripout | | 4.2 | 1.0 | 0.9 | 3.8 | 8[16] | 5.6[16] | 2.1 | 2.0 | 1.5 | 16 | 6.8 | | 0.3 | | 13 |

[12] *R & H* equals ring and horn.

[13] No. 2 circuit—*R & H*.

[14] *R & H* on No. 1—*R & R* on No. 2

[15] Storms reported at one end only.

[16] Assuming same number of storms at both ends of line.

[17] Only one line.

[18] Also F.O. on one pin insulator at tap-off.

[19] Reported at two ends only.

decreased from 1926 to 1931 (excluding 1929 which was a bad lightning year) it is observed that the percentage of outages involving both lines has increased. On the other hand, it will also be noted that the total miles of two circuit lines on the system has also increased. It might be deduced from this fact that the increase in the size of the system, that is, the connected kva capacity had also increased. This, in fact, has been the case. A 165,000-kva generator was installed in the spring of 1929 at the Philo Plant which is roughly at the center of the transmission system; and in August 1929 an interconnection with another large system was placed in continuous service at the extreme western end of the system. It is believed that this increased system capacity has sufficiently maintained voltage in some cases so that line lightning flashovers which previously had in some cases not developed into short circuits on the line, did after 1929 become a factor in actually tripping out the second circuit.

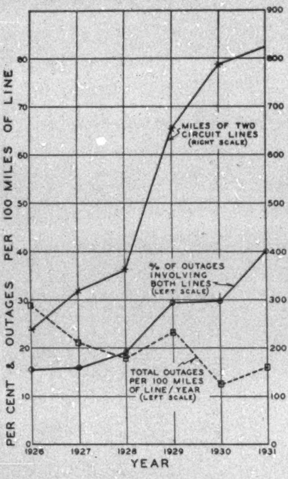

Fig. 2—Lightning Performance of Two-Circuit Lines

## Line Damage

The record of damage to line wires, insulators, and arcing protection is given in Table I for each line. The fact that the "cases of damage per line outage" runs in the order of 0.2 to 2.0, where the records are complete, with an average of approximately 1.1 shows that the majority of line tripouts are accompanied by one but not more than two flashovers. This indicates as would be expected that line flashover is confined close to the point of origin of the electrical disturbance. The fact that comparatively few insulators, burned conductors, or hardware have been observed, and rarely of sufficient importance to require servicing, shows that the arcing protection has been very effective in preventing severe damage to the line. The protection afforded by the rings to line insulators is in line with prediction and past experience.

During the three years' operation 1929-30-31, no trouble from lightning on the 132-kv lines has made necessary holding the line out of service longer than the time necessary to reclose the switch.

## Station Apparatus Damaged

The three-year (1929-30-31) records of damaged apparatus at substations over the entire interconnected 132-kv system shows that lightning damaged one transformer, nine coupling condensers which were used for the communication system, and one insulator on the lightning arrester gap at one substation. At the substation where the transformer was damaged, it is important to note that lightning arrester protection had been provided. The failure of this large number of coupling condensers has been very definitely fixed as due to a defect in the inherent design of the apparatus, as at the time these condensers were installed no attempt had been made, due to the complete lack of reliable impulse data, to coordinate their insulation strength with that of the other station apparatus on a lightning basis.

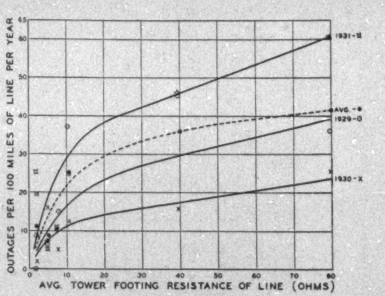

Fig. 3—Effect of Tower Footing Resistance on Line Outages

Lima-Fort Wayne
Lima-Fostoria
Muncie-Anderson
Philo-Canton
Glenlyn-Roanoke
Roanoke-Reusens
Turner-Logan
Twin Branch-Benton Harbor
Twin Branch-Fort Wayne
Philo-Crooksville

It should be noted that the use of lightning arrester protective equipment at each of the substations did not render all the station apparatus immune to lightning failure. It is quite true, however, that the record of only one transformer failure from lightning in three years in this large number of stations shows that the stations are operating with a high degree of protection against lightning although this protection is not 100 per cent perfect.

### The Effect of Tower Footing Resistance

In a paper describing the 1929 lightning experience,[1] the effect of tower footing resistance of lines equipped with ground wires was fully discussed, and it was pointed out that if a ground wire is to offer a high degree of protection against lightning flashover at the tower, the tower footing resistance must be relatively low—in the order of 5 ohms or less. Some further light is thrown on this phase of the problem by the analysis made for the last three years, from this point of view.

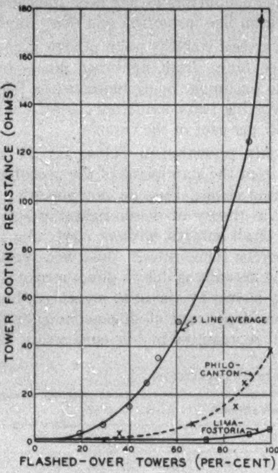

Fig. 4—Tower Footing Resistance Where Flashover Occurred 1929-30-31

Philo-Canton
Roanoke-Reusens
Lima-Fostoria
Glenlyn-Roanoke
Turner-Logan

The relation between the average tower footing resistance of ten different lines and the number of outages per one hundred miles of line per year for three years is shown in Fig. 3, each plotted point representing the specific performance of a particular line plotted against the average tower footing resistance of that line. The average performance for the three years' operation is shown by the dotted curve. This, as well as the three individual curves, shows a distinct reduction in outages as the tower footing resistance is lowered. The reduction of tower footing resistance from 80 ohms to 40 ohms results in a decrease in outages of 13 per cent; on the other hand, a 50 per cent reduction in tower footing resistance from 10 ohms to 5 ohms reduces the outages 35 per cent. Since Fig. 3 gives data for ten different lines over a three-year period, the benefits indicated from the lower tower footing resistance cannot be laid to mere chance.

To trace thoroughly the effect of tower footing resistances, the resistance values at towers where flashovers have actually been observed have been studied for five lines and are shown graphically in Fig. 4. These curves give the highest value of tower footing resistance encountered in any percentage group of flashed towers both for two separate lines and for all the five lines indicated. It will be noted, first, that tower footing resistances, even as low as 5 ohms, do not make a line immune to flashover from lightning. Second, on the five lines for which data have been summarized in Fig. 4, 50 per cent of the flashovers occurred at towers having a footing resistance less than 30 ohms, and 30 per cent of the flashovers occurred at towers with a footing resistance less than 10 ohms. Over 20 per cent of the flashovers occurred at towers with footing resistances less than 5 ohms.

Analyzing the effect of tower footing resistance still further, Fig. 5 shows that where the tower footing resistance is low there is less disturbance to the line from lightning storms. For example, with the tower footing resistance of 2½ ohms there has occurred only one line outage for every 10 storms. Where the average tower footing resistance of the line has been 40 ohms there has been one outage for every lightning storm observed. As the tower footing resistance becomes higher the outages per storm, or the storms through which the line can ride without an outage, become less than one, that is, on an average over a period of time, more than one outage occurs per lightning storm.

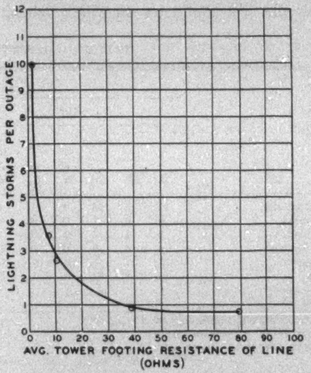

Fig. 5—Lightning Storms per Line Outage per 100 Miles of Line per Year. 3 Year Average

Philo-Canton
Roanoke-Reusens
Turner-Logan
Glenlyn-Roanoke
Lima-Fostoria

Total storms reported at terminals

| | |
|---|---|
| 1929 | 261 |
| 1930 | 103 |
| 1931 | 150 |

## LOCATION OF LINE TROUBLE

In an attempt to determine how lightning has initially come on the line an analysis has been made of the location of trouble on the line conductors by three methods: first, by means of physical inspection of the line (tower climbing inspection), second, by relay target indications, and third, in one special case, by an automatic oscillograph. In Table III is given the record of line flashovers on top, middle, and bottom conductor as observed from the line inspection on five different lines. The same type of data is given in Table IV from the record obtained from the relay targets; and in Table V are given similar data obtained from automatic oscillograph records. These tables show a preponderance of single-phase trouble, 86.4 per cent being recorded by the line inspection, 64.3 per cent by the relay target indications, and 60.6 per cent by the oscillograph. Thus it appears that the majority of lightning troubles result in single-phase fault currents but roughly divided about equally on top, middle, and bottom conductors. This of course does not necessarily mean that these troubles start as single-phase lightning faults, as it has been proven in the past that system power current will not, under certain conditions, follow. For example, if a conductor on which lightning flashover takes place is at or near zero voltage of the normal 60-cycle wave power current does not follow. Undoubtedly the data in Table V are far more accurate than in Tables III and IV as Table V is based on data obtained from an oscillograph located at Glenlyn whereby the phase voltages of the system were recorded. It should be noted, however, that the faults are located in the same general position with respect to top, middle and bottom conductors as has been indicated by data obtained from line inspection and relay targets.

From a system stability point of view it appears that three-phase faults from lightning causes occur very rarely, the maximum being indicated as 8.8 per cent. Faults involving two conductors comprise a maximum of about 27 per cent of the trouble.

If the data presented in Tables III, IV and V are analyzed from the standpoint of the probable origin of the lightning stroke, they do not present a clear cut case for the theory of direct lightning strokes being the cause of all outages, without stretching the theory to a dangerous tenuousness. Just what percentage of the outages actually is due to direct stroke is of course not clearly shown by the data presented, but the fact that of the 74 per cent of single-conductor flashovers, 23 per cent represented middle conductors, 22 per cent

TABLE III—LOCATION OF TROUBLE BY LINE INSPECTION

| | Conductors affected | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929 | | | | | | | 1930 | | | | | | | 1931 | | | | | | |
| Line | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & B. | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & B. | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & B. |
| Glenlyn-Roanoke | 16 | 8 | 16 | 0 | 1 | 4 | 2 | 8 | 14 | 10 | 3 | 0 | 3 | 0 | 8 | 9 | 10 | 2 | 0 | 1 | 0 |
| Lima-Fostoria | 6 | 0 | 1 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | |
| Philo-Canton | 8 | 1 | 3 | 0 | 0 | 1 | 1 | 3 | 2 | 1 | 0 | 0 | 1 | 0 | 6 | 2 | 1 | 2 | 0 | 1 | 0 |
| Roanoke-Reusens | 4 | 4 | 9 | 0 | 0 | 0 | 3 | 10 | 8 | 10 | 0 | 0 | 4 | 0 | 4 | 6 | 13 | 2 | 2 | 2 | 0 |
| Turner-Logan | 11 | 1 | 1 | 0 | 0 | 0 | 0 | 8 | 2 | 0 | 0 | 1 | 0 | 0 | | | | | | | |
| Total | 45 | 14 | 30 | 0 | 1 | 5 | 6 | 33 | 26 | 21 | 3 | 1 | 8 | 0 | 18 | 17 | 24 | 6 | 2 | 4 | 0 |
| Total for 3 years | | | | | | | | 96 | 57 | 75 | 9 | 4 | 17 | 6 | | | | | | | |
| Per cent of total | | | | | | | | 36.4 | 21.6 | 28.4 | 3.4 | 1.5 | 6.4 | 2.3 | | | | | | | |

Per cent involving one phase only 86.4.
Per cent involving two phases only 11.3.
Per cent involving three phases only 2.3.

TABLE IV—LOCATION OF TROUBLE BY RELAY TARGET INDICATION

| | Conductors affected | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1929 | | | | | | | 1930 | | | | | | | 1931 | | | | | | |
| Line | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & B. | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & M. | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. B. & M. |
| Glenlyn-Roanoke | 7 | 7 | 7 | 8 | 1 | 4 | 0 | 5 | 5 | 2 | 3 | 0 | 1 | 0 | 4 | 12 | 4 | 3 | 5 | 4 | 5 |
| Lima-Fostoria | | | | | | | | | | | | | | | 3 | 0 | 0 | 1 | 1 | 0 | 1 |
| Philo-Canton | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 6 | 5 | 2 | 0 | 0 | 0 | 0 |
| Roanoke-Reusens | 2 | 0 | 3 | 0 | 1 | 0 | 2 | 1 | 4 | 6 | 1 | 1 | 1 | 0 | 3 | 4 | 9 | 2 | 3 | 5 | 9 |
| Turner-Logan | 5 | 6 | 3 | 0 | 0 | 3 | 1 | 1 | 0 | 0 | 1 | 2 | 1 | 0 | 3 | 4 | 4 | 1 | 1 | 0 | 0 |
| Total | 15 | 13 | 14 | 9 | 3 | 7 | 3 | 9 | 10 | 9 | 5 | 3 | 3 | 0 | 19 | 25 | 19 | 7 | 10 | 9 | 15 |
| Total for 3 years | | | | | | | | 43 | 48 | 42 | 21 | 16 | 19 | 18 | | | | | | | |
| Per cent of total | | | | | | | | 20.8 | 23.2 | 20.3 | 10.0 | 7.8 | 9.2 | 8.7 | | | | | | | |

Per cent involving one phase only 64.3.
Per cent involving two phases only 27.0.
Per cent involving three phases only 8.7.

bottom conductors and only 29 per cent top conductors, makes it very difficult to explain how direct lightning strokes are responsible for all outages on the lines of this particular system.

### COUNTERPOISES AND GROUND RODS

To show the effect of ground rods driven at the base of a tower in reducing the tower footing resistance, Table VI has been compiled. At each tower five 1 inch by 20 feet galvanized rods were driven and each rod treated with 100 lb of rock salt. The reduction in tower footing resistance by the installation of these rods is approximately 50 per cent, the ratio of resistance before and after installation of the rods being, for the 20 towers, 52 per cent.

TABLE V—LOCATION OF LINE FLASHOVERS BY GLENLYN OSCILLOGRAPH RECORDS 1930-1931 SINGLE LINE OUTAGES

| Line | T. | M. | B. | T. & M. | T. & B. | B. & M. | T. M. & B. |
|---|---|---|---|---|---|---|---|
| Glenlyn-Roanoke | 5 | 5 | 3 | | | | |
| Roanoke-Danville | 3 | 1 | 3 | | 4 | 2 | 2 |
| Switchback-Saltville | 2 | 2 | | 1 | | | 1 |
| Total | 10 | 8 | 6 | 1 | 4 | 2 | 3 |
| [2]Per cent of total by osc. | 29.5 | 23.5 | 17.6 | 2.9 | 11.8 | 5.9 | 8.8 |
| [3]Per cent of total by inspection | 36.4 | 21.6 | 28.4 | 3.4 | 1.5 | 6.4 | 2.3 |
| [4]Per cent of total by relay targets | 20.8 | 23.2 | 20.3 | 10.0 | 7.8 | 9.2 | 8.7 |
| Average | 28.9 | 22.8 | 22.1 | 5.4 | 7.0 | 7.2 | 6.6 |
| Per cent single line faults | 73.8 | | | | | | |
| Per cent two line faults | 19.6 | | | | | | |
| Per cent three phase faults | 6.6 | | | | | | |

[2]From Table V (1930-1931).
[3]From Table III (1929-30-31).
[4]From Table IV (1929-30-31).

The reduction in tower footing resistance by the use of counterpoises is shown in Table VII. The counterpoise in this case consisted of 4 galvanized iron strips approximately 1/16 in. by 2 in. in cross section, two lengths each extending 150 ft away from the tower in opposite directions and parallel to the line, and two lengths extending similarly at right angles to the line, each being approximately 40 feet long. The total length of strips connected to each tower is therefore 380 feet. This metallic strip was buried approximately 18 inches in the ground where soil conditions permitted. The reduction in tower footing resistance is shown from Table VII to be exactly 50 per cent.

Since these ground rods and counterpoises have been in service only a comparatively short time, the beneficial effects which are expected from their use have not as yet been proved. The limited data available, however, seem to indicate that the counterpoise in particular is giving a degree of protection against lightning considerably in excess of what is indicated by the mere numerical reduction in tower footing resistance.

TABLE VI—EFFECT OF GROUND RODS* IN REDUCING TOWER FOOTING RESISTANCE DEEPWATER-PLEASANTVILLE

| Tower No. | Resistance (ohms) No ground rods—$R_1$ | Resistance (ohms) with ground rods—$R_2$ | $R_2/R_1$ % |
|---|---|---|---|
| 281 | 90 | 63 | 70 |
| 282 | 140 | 66 | 47 |
| 283 | 150 | 103 | 68 |
| 284 | 230 | 92 | 40 |
| 285 | 240 | 100 | 42 |
| 286 | 200 | 108 | 54 |
| 287 | 250 + | 97 | 39 |
| 288 | 165 | 75 | 45 |
| 289 | 70 | 48 | 68 |
| 290 | 250 + | 97 | 39 |
| 291 | 210 | 85 | 40 |
| 292 | 205 | 85 | 41 |
| 293 | 145 | 80 | 55 |
| 294 | 95 | 95 | 100 |
| 295 | 240 | 110 | 46 |
| 296 | 230 | 53 | 23 |
| 297 | 110 | 85 | 77 |
| 298 | 60 | 37 | 62 |
| 299 | 200 | 90 | 45 |
| 300 | 224 | 104 | 47 |
| Avg | 175 | 84 | 52 |

*100 lb of salt per 20 ft rod and 5 ground rods per tower.

TABLE VII—EFFECT OF COUNTERPOISES IN REDUCING TOWER FOOTING RESISTANCE GLENLYN-ROANOKE LINE—1932

| Tower No. | Resistance (ohms) no counterpoise–$R_1$ | Resistance (ohms) with counterpoises–$R_2$ | $R_2/R_1$ % |
|---|---|---|---|
| 6 | 91 | 62 | 68 |
| 6A | 322 | 77 | 24 |
| 7 | 37 | 14 | 38 |
| 8 | 198 | 75 | 38 |
| 9 | 47 | 20 | 43 |
| 10 | 7.5 | 5.0 | 68 |
| 10A | 16.5 | 8.5 | 51 |
| 10B | 16.5 | 10 | 60 |
| 11 | 30 | 15 | 50 |
| 12 | 20 | 11 | 55 |
| 13 | 67 | 42 | 63 |
| 14 | 90 | 32 | 36 |
| 15 | 17.5 | 10 | 57 |
| 16 | 55 | 23 | 42 |
| 17 | 37 | 19 | 51 |
| 18 | 75 | 42 | 56 |
| 19 | 62 | 40 | 65 |
| 20 | 65 | 32 | 49 |
| 21 | 46 | 22 | 48 |
| 22 | 30 | 10 | 33 |
| Avg | 66 | 28 | 50 |

### CONCLUSIONS

1. Reasonably good protection against lightning has been afforded station apparatus on this system by the use of lightning arresters and grading insulation at the substation as is evidenced by the failure of only one power transformer during the three years covered by this investigation. The fact that a transformer failed although protected by a lightning arrester still shows that there is something to be accomplished before we can provide 100 per cent protection to station apparatus.

2. Grading shield protection on the line itself has proved very effective as evidenced by the relatively small number of damaged insulators and burned conductors—troubles which in no case have required a line to be kept out of service for repair. Line inspections have shown that the grading shields have taken the power arc in the majority of cases.

3. Transmission line outages are materially reduced by reduction of tower footing resistance. However, tower footing resistances as low as 3 ohms do not guarantee immunity from lightning outages even though the lines are equipped with an overhead ground wire.

4. In case of two circuit lines the per cent of outages affecting both lines increases as the size of the system (kva generating capacity) is increased.

5. No evidence of direct hits to the line wires themselves between towers has been found. (Previous to the installation of a ground wire on the Lima-Twin Branch Line evidence of burned conductors in the span was reported.)

6. Increasing line insulation considerably on lines of low operating voltage (132-kv insulation for 33-, 44-, and 66-kv lines) has not been sufficient to prevent follow-up current and consequent line outage in case of lightning flashover.

7. Lightning flashovers on a typical group of lines causing power follow-up resulted in single-phase faults in approximately 73.8 per cent of the cases (divided as follows: top 28.9 per cent, middle 22.8 per cent, bottom 22.1 per cent) two-phase faults in 19.6 per cent of the cases, and three-phase faults in 6.6 per cent of the cases. With this record, it is hard to justify the theory that all or even the majority of lightning outages on these lines have been the result of direct lightning strokes to the lines, overhead ground wires, or towers.

8. The only line using two overhead ground wires directly above the transmission circuits has throughout a period of years shown an excellent performance even though the average tower footing resistance of the line was 12 ohms. On two other lines using two ground wires, one directly below the other, the outage per one hundred miles of line per year is less than the average although still not as good as that line where both ground wires are above the transmission circuits.

9. The large number of lightning outages per one hundred miles of line per year on wood pole lines operated at 132-kv seems to indicate that the degree of lightning protection assumed to be possible with the use of wood or lightning insulation has not been obtained in this case. It may be, however, that since in both cases these wood pole lines are not equipped with the overhead ground wire, that this may account in part for the excessive number of line outages in these cases.

### ACKNOWLEDGMENT

The author wishes to acknowledge the help and encouragement received from the organizations of each of the operating companies whose transmission systems are described in this paper and who have cooperated in the gathering of the data and in the investigations described. He also wishes to acknowledge the valuable work of Mr. I. W. Gross in the gathering, correlating and development of the data and the help in the preparation of this paper.

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## Discussion

**Everett S. Lee:** There is a great difference between the situation today and that in 1925, which may be taken as the year when the last romance with lightning by the electrical engineers began. That was the year of many storms; the wreck of the Shenandoah came about that time.

Mr. Sporn in a paper in the TRANSACTIONS for 1926[1] says: "While these troubles were occurring, it was impossible to get any accurate data as to what was happening. Lines were flashing over, insulators were being shattered, the conductor was being burned, the field forces were too busy trying to place the line in an operating condition with minimum delay to be able to give very much attention to the details of what was happening. Things were happening so thick and fast that there was no opportunity to stop and consider the matter calmly. With the approach of the end of the lightning season a little more time could be taken to determine what had actually happened to make an intelligent analysis." Most of us at one time or another have found ourselves in the midst of kindred troubles so that this graphic description finds a human response within us.

Coincidently with the need for analysis, which was evident generally, came the necessary tools, for Messrs. Cox and Legg presented a paper[2] at Saratoga in 1925 telling of the klydonograph and the use of Lichtenberg figures as a means for measuring surge voltages. At the same convention, Messrs. McEachron and Wade gave a paper[3] describing the application of the cathode-ray oscillograph to time-lag studies of sphere spark gaps, technique in the same field.

Then started the romance of the engineer with lightning. Out into the field they went on many different systems—east, west, north and south, equipped with devices advancing year by year. Klydonographs and surge-voltage recorders were dotted thickly along transmission lines to measure the voltages there. Up went the recorded voltages, 1 million, 2 million, 3 million, 5 million. The cathode ray oscillograph, laboratory instrument of the scientists was taken out into its mountain home to await the coming of the lightning which the observers prayed would come in abundance and which the operators prayed would stay away with its devastation. But it did come and the cathode ray oscillograph, waiting, revealed the wave form of the voltages measured by the surge-voltage recorders. This brought microseconds into the picture and the engineers talked glibly of 1 microsecond and 10 microseconds, and yesterday and today we are talking standardization of these values as we would talk standardization of volts and ohms and amperes and degrees.

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[1] *Lightning and Other Experiences*, by M. L. Lindeband and P. Sporn, A.I.E.E. TRANS., Vol. XLV, 1926, p. 770.

[2] *The Klydonograph and Its Application to Surge Investigation*, A.I.E.E. TRANS., Vol. XLIV, 1925, p. 857.

[3] *Study of Time Lag of the Needle Gap*, A.I.E.E. TRANS., Vol. XLIV, 1925, p. 832.

And so the romance continued. With the measurements of lightning voltages came the need for rating the severity of lightning, so the storms were counted, and the lightning severity meter was devised and used. Then came the wish to know more about the currents involved, and the lightning stroke recorder was developed and more data appeared along the transmission lines, and we began to talk of 50,000 and 1,000,000 amperes. And in the paper by Messrs. Lewis and Foust, we find an intensive study of the tower currents from lightning stroke recorded records and a new instrument referred to, the surge-crest ammeter, described elsewhere in the technical press, used for an extension of this work.

With the gathering of all these data and the intensive analysis accompanying it, the transmission engineers began to talk of new schemes, the counterpoise came into the picture to supplement the ground wire; lightning protection wires appeared, and through it all, the ground wire of old rode safely through the storm, being rendered even more effective by these devices. New words came into prominence, rationalization and coordination, and now these are subjects for standardization. Direct strokes and induced strokes became the subject of conversations, papers and discussions, and today the knowledge of these is more certain, though apparently not yet the subject for standardization.

Through all of this romance, there has been brought to the A.I.E.E. the results of those who have worked so wonderfully and so effectively in this field. Their reward is their satisfaction of a work well done. And unlike that of Mr. Sporn's experiences related in his 1926 paper, we find in this present paper these words:

"The fact that comparatively few insulators, burned conductors, or hardware have been observed, and rarely of sufficient importance to require servicing, shows that the arcing protection has been very effective in preventing severe damage to the line. The protection afforded by the rings to line insulators is in line with prediction and past experience.

"During the three years' operation, 1929-30-31, no trouble from lightning on the 132-kv lines has made necessary holding the line out of service longer than the time necessary to reclose the switch."

These are some of the results of the work which came after the intelligent analysis. All problems have not yet been solved, but we believe they are on a substantial basis.

In looking over some of the reports forming a basis of these papers, the writer found the following tabulation:

| Year | |
|---|---|
| 1927 | 100 |
| 1928 | 100 |
| 1929 | 130 |
| 1930 | 100 |
| 1931 | 70 |
| 1932 | 50 |

These are storm severity records for one of the large transmission systems of the east based on storm reports and line operation. Similar figures given by Mr. Sporn for his system do not show the same relative severity decrease in the last two years, even though his line performance record shows more satisfactory attainment. These data are a necessary part to the whole picture in order that proper credit may be given to the design of the line and associated apparatus throughout in view of the line performance. There is still much room for advance in the design of instruments for recording lightning severity, and though the problem is difficult, and the expense great, it is to be hoped that success will ultimately be achieved in this regard.

**A. O. Austin:** The very complete information upon the operating records of the American Gas and Electric Company's system is worth many times the expense and time required to collect and compile, as records of this kind eventually make it possible to compare different types of construction and methods of operation. What we really need is a comparative reliability or performance index for different types of construction, so that new lines can be designed and installed upon a better engineering basis. There are so many factors involved that it would seem almost impossible to devise a scheme of analysis which would provide an operating index. However, continued work upon a scheme shows that much can be accomplished when checked with operating results such as those given by Mr. Sporn, and it is hoped that the Institute will have the benefits of further reports of this kind.

The effect of high towers in increasing the number of hits to the system as well as the length of span in increasing the impedance which affects the drainage of the charge for a direct hit all show their effect upon operation, other conditions being equal. It would seem that high ground capacitance rather than a low ground resistance is an essential. The presence of water in the ground lowers the ground resistance but greatly increases the capacitance. This is of material benefit not only in absorbing the charge but in lowering the effective height or exposure of the line. High ground capacitance may be obtained even for conditions where a low ground resistance is not possible by the use of a counterpoise or a grid system radiating from the tower.

It has long been evident that a line may have an entirely different exposure for negative and positive strokes. While in general negative strokes are much fewer their tendency to cause tripouts is much greater as the current values probably are very much higher in most cases, so that the impedance drop may be a factor which probably should be given more attention. Shortening the span not only reduces the impedance in the ground wire but makes it possible to lower the effective height of the system. A relatively low transmission line without ground wire protection possibly may have fewer tripouts, even though every direct hit to the system causes a tripout, than a system having a greater exposure but in which a portion of the hits only causes tripouts.

Reducing the impedance of ground wire systems by shortening spans, cross connecting the ground wires, and by providing grids or counterpoises certainly will be given much more attention in the future than in the past. This together with the decreased exposure will tend to provide much higher reliability.

Mr. Sporn has pointed out that the possibility of trouble due to induced voltage cannot be overlooked. Fortunately the gradient affecting the transmission line is not very high for most lightning discharges even in the vicinity of a direct hit. However, where the gradient is high the release of a bound charge easily can cause flashover, as shown by Mr. Sporn's report. Very high ground wires are costly and increase the exposure, and when they are connected to the towers it must be remembered that the flashover voltage of the insulator must be depended upon to prevent a tripout unless the impedance of the path of the discharge to ground is very low. The path taken by a discharge following a direct hit indicates that the wave fronts are exceedingly steep.

On large interconnecting systems it frequently is difficult to limit the normal frequency current from phase to ground, but where this can be accomplished a flashover may not necessarily result in a tripout, as the negative coefficient of the arc is an important factor in maintaining a path of low resistance to ground. Any reduction in the normal frequency current tends to allow quenching of the arc due to radiation. Increasing the effective flashover voltage and limiting the normal frequency current by resistance or reactance in the neutral will do much to quench the normal frequency arcs tending to follow a flashover from lightning, and undoubtedly can be used to improve the operation for many systems.

It is to be hoped that more operating records will be available, so that the effect of various factors upon the relative performance can be used to obtain an operating index which will be a guide to designing as well as the treatment of existing lines.

**V. M. Marquis:** In the past it has been necessary to rely to a great extent upon tower climbing inspections and relay targets to determine the phase or phases involved in any flashover due to lightning. Relay targets are not always positive in their action: and tower climbing inspections have the disadvantages that (at least in some districts where inspections are rather infrequent) it is difficult definitely to correlate visual damage with specific outages.

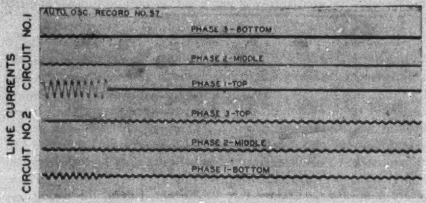

Fig. 1—Single-Circuit Outage Due to Lightning

No. 1 circuit—10 cycles to clear
Glen Lyn-Roanoke 132-kv double-circuit line, August 29, 1932—11.06 a. m.

An additional means of checking the phase location of damage on transmission lines has been made possible with the development of the latest type of automatic magnetic oscillograph. This has overcome the limitations of the older types with respect to the slow starting characteristics and the necessity of changing films after each or at best after a limited number of records. Also, with the new type of oscillograph, all but about the first half cycle of the follow-up current is recorded, and such a record gives a most definite and positive means for determining the phases in trouble and the sequence of events after the appearance of the dynamic follow-up current. Such an instrument should prove very beneficial in the study of lightning from the standpoint of the follow-up normal frequency currents that result from a lightning flashover.

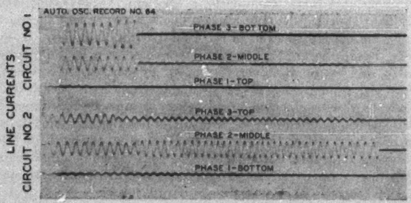

Fig. 3—Double-Circuit Outage Due to Lightning

No. 1 circuit—13 cycles to clear
No. 2 circuit—46½ cycles to clear
Glen Lyn-Roanoke 132-kv double-circuit line, September 1, 1932—1.32 p. m.

During the early part of 1932 an automatic oscillograph of the latest type was installed at Glenlyn and connected so as to measure the 6 line currents on the double-circuit Glenlyn-Roanoke 132-kv line. Records were obtained of all outages during the past year, and some of these records should prove of interest.

Fig. 1 shows a single-circuit outage in which a flashover occurred on the top conductor of circuit No. 1. It will be noted that there was no follow-up current on any of the other conductors. It would appear that a direct stroke to this top conductor might explain this outage.

Fig. 2 shows a single-circuit outage due to lightning, in which the follow-up current existed only in the bottom conductor of circuit No. 2. This flashover can reasonably be accounted for by either a direct or induced lightning stroke.

Fig. 3 shows a double-circuit outage in which both circuits evidently flashed over at about the same time. This flashover involved the middle conductor of both circuits and the bottom conductor of circuit No. 1. This particular flashover can be accounted for by an induced lightning stroke, but it is not so readily accounted for if a direct stroke to the system is assumed.

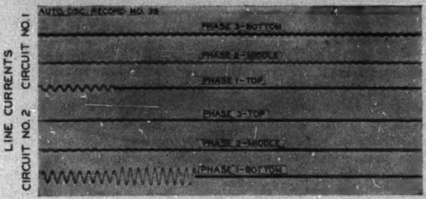

Fig. 2—Single-Circuit Outage Due to Lightning

No. 2 circuit—18½ cycles to clear
Glen Lyn-Roanoke double-circuit line (132 kv), July 14, 1932—5.07 p. m.

In Fig. 4 is shown another outage that eventually involved both circuits. The interesting point brought out by this oscillogram is that the follow-up current which started on the middle conductor of circuit No. 2 cleared before a short circuit took place on the top conductor of circuit No. 1. Some ¾ of a cycle elapsed between the time the arc went out on circuit No. 2 and started on circuit No. 1. In this particular case we have no way of definitely knowing whether the second flashover resulted from the first, or whether there were actually two separate and distinct lightning discharges. However, it would appear that the trouble on the top conductor of circuit No. 1 was a direct result of the trouble on the middle conductor of circuit No. 2 and not initiated by the original flashover.

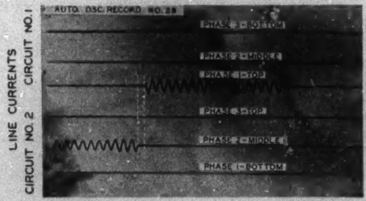

Fig. 4—Double-Circuit Outage Due to Lightning

No. 2 circuit—12 cycles to clear
No. 1 circuit flashed over ¾ cycle after circuit No. 2 cleared
Glen Lyn-Roanoke double-circuit line (132 kv), July 6, 1932—1.32 p. m.

A physical inspection of the line or a report based on relay targets would, of course, list this as a double-circuit outage. Furthermore, it would probably be explained as a direct stroke to the top conductor and such an explanation would, of course, be incorrect.

In general, it has been found that the oscillographic records agree with relay targets as to the location of outages with respect to phases, and that the totalized outages with respect to phases are in fairly close agreement as recorded by the oscillograph and by tower-climbing inspection reports. However, by proper use of the oscillograph all possibility of doubt can definitely be removed and a positive record obtained of the sequence of events during the outage.

There were no double circuit outages on the Glenlyn-Roanoke line that could be attributed to an overload or unstable condition; that is, there was no evidence of an outage of one circuit resulting in a disturbance that caused the second circuit to trip. This is definitely shown by the oscillograph records obtained during the past lightning season. A study of the outages on all other double-circuit lines of the system has led us to believe that none of the double-circuit outages so far experienced has resulted from power swings or straight overloading of the second circuit due to tripping of the first.

**F. W. Peek, Jr.:** This paper contains much more fundamental information than is apparent on a casual reading. This is illustrated by referring particularly to Fig. 5. This figure shows that even when the tower footing resistance is as low as 3 ohms, one outage can be expected in every ten storms and that the lightning outages per storm increase until the footing resistance reaches 40 ohms. At higher resistances the outages do not increase. It would appear that the particular outages affected by resistance are due to direct strokes since the lower values of resistance would not reduce the efficiency of the ground wire. It is possible from these two points on the curve to get an approximate idea of the minimum and maximum values of direct stroke currents. We have found that the voltage $V$ on an insulator due to a direct stroke to the tower is

$$V = 0.8\, IR$$

where $I$ is the lightning current and $R$ the tower footing resistance.

The insulator sparkover of this line is approximately 1,200,000 kv. Therefore, the current is

$$I = \frac{1{,}200{,}000}{0.8\, R} = 500{,}000$$

Where 1 outage occurs in 10 storms, the footing resistance is 3 ohms. Therefore a maximum current of 500,000 amperes would be expected in one direct stroke to the line in 10 storms. From the other end of the scale, it follows that the minimum direct stroke current for lightning storms equals

$$I = \frac{1{,}200{,}000}{0.8 \times 40} = 37{,}500 \text{ amperes}$$

These values are very approximate, it is true, but they indicate the order of the current range of direct strokes and, incidentally, are of the same order as those obtained by direct measurements.

# Impulse and Dynamic Flashover Studies of 26-Kv Wood Pole Transmission Construction

BY A. S. BROOKES* Associate, A.I.E.E.      R. N. SOUTHGATE* Associate, A.I.E.E.      and      E. R. WHITEHEAD† Associate, A.I.E.E.

***Synopsis.**—This paper presents the results of a series of laboratory tests made with a million volt surge generator and 60-cycle high-voltage testing equipment on unit pole transmission construction now in standard usage on a large 26-kv transmission system. Actual impulse curves are given for several types of straight span pole top construction. Basic values of impulse flashovers are presented which should facilitate coordination of impulse insulation between poles of any similar transmission lines, aid in applying protective gaps, and furnish a guide to the comparative impulse strength of both present and new types of construction. Defects in present design standards and possible improvements are discussed.*

*An analysis of the factors governing the development of a power arc following impulse sparkover and corresponding experimental data showing the extent of occurrence of such arcs are presented. The paper concludes that reliance upon air or wood separations within the usual physical limits to prevent lightning outages will be unsatisfactory, and discusses the application of protective measures.*

* * * * *

## INTRODUCTION

THIS study has been made on the 26-kv wood pole transmission construction of the Public Service Electric and Gas Company in cooperation with the Westinghouse Electric and Manufacturing Company. The objects of this investigation were to secure adequate data to estimate the relative lightning performances of present and proposed construction.

## EQUIPMENT

The series of tests was made by subjecting actual unit pole assemblies to impulse and 60-cycle voltages, separately and simultaneously. The test equipment consisted of a million volt surge generator[1] and a 60-cycle, 750-kv test set.

## TEST WAVE

For all tests a 0.5-0.75/60 positive wave was used. No corrections were made for barometer or humidity.

In plotting volt-time curves[5] of combinations involving wood, the a-c flashover voltages sometimes exceeded the impulse. This irregularity is ascribed to the variation in wood specimens, the difference in path of the impulse arc at long and short time flashovers; and to the difference in path of the impulse and dynamic flashovers. However, as the 60-cycle datum point is taken on the steep front of the wave, a large variation in this value will change the impulse curve but slightly.

In applying the volt-time curves given in this paper, the regions below one microsecond should be considered approximate since the measuring circuit may have distorted the wave front slightly and the a-c flashover values may be erratic.

## 60-CYCLE AND IMPULSE TESTS ON COMPONENT PARTS OF WOOD POLE TOPS

It was desired to obtain some simple basic means of comparing pole top flashover values. Unfortunately preliminary tests showed that when wood is involved, no workable relationship exists between impulse and a-c values. Accordingly impulse tests were made on the component parts of pole top assemblies so that the data secured could be used to compare other pole tops.

Sixty-cycle flashover tests were made on wooden crossarms and on each component assembly. Fig. 1 shows the range of values for dry seasoned arms, for unseasoned arms and for wet arms, with their averages.

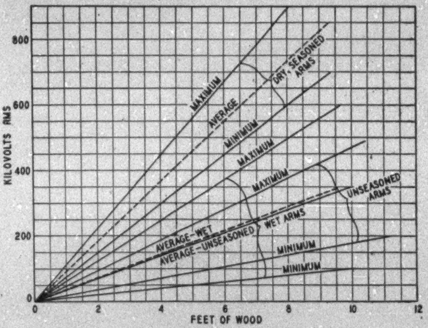

FIG. 1—60-CYCLE FLASHOVER VALUES FROM TESTS ON DRY, WET, AND UNSEASONED FIR CROSSARMS

The results on crossarms in combination with porcelain are given with the impulse curves.

These 60-cycle crossarm test results may be summarized as follows:

1. Both unseasoned and wet wood have negligible a-c insulation strength.
2. Creosoting does not appreciably alter the 60-cycle insulation of wood.
3. The 60-cycle values vary so greatly for different specimens and conditions that they give no indication of the impulse strength.

In securing volt-time impulse curves, one terminal was grounded. This method gives actual impulse flash-

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[1] For references see bibliography.

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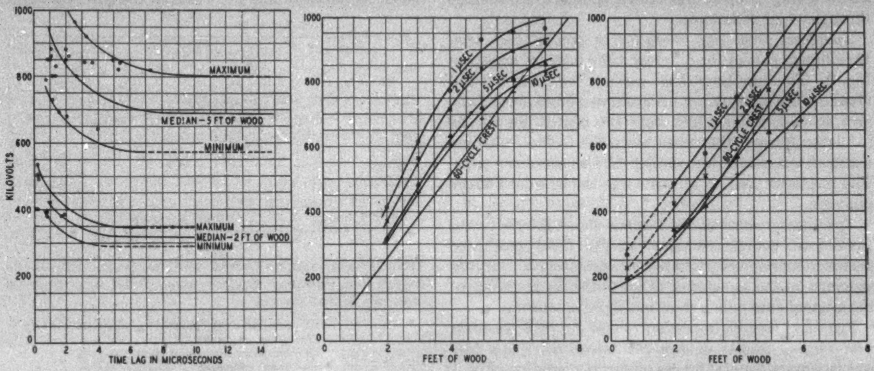
over voltages when the arc is from any conductor to a ground but the values give only comparative impulse strengths for flashover between conductors. For the latter case, it would be necessary to consider, among other factors, the induced voltage on the second conductor.

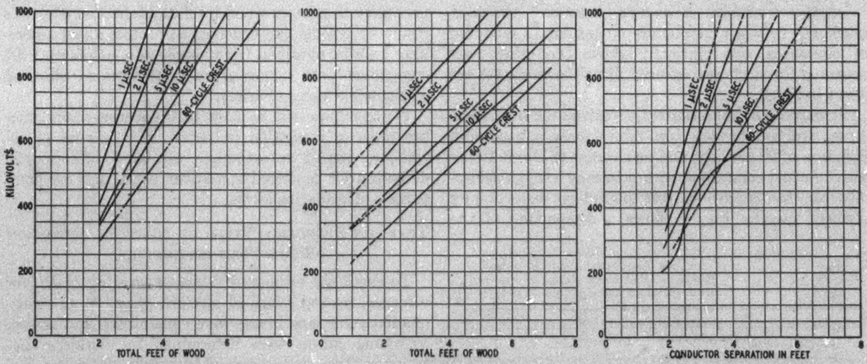
No data are here given for sparkovers in midspan, as adequate information on air breakdown is available. The following pole top component parts were considered essential.



Volt-time curves for fir crossarms

Breakdown curves for fir crossarm alone

Breakdown curves for fir crossarm and one 45-kv porcelain pin insulator



Breakdown curves for 2 insulators mounted on the same arm, spacing varied

Breakdown curves for 2 insulators mounted on a 10-ft arm, with various brace lengths (see Fig. 3)

Breakdown curves for 2 insulators each mounted on a separate crossarm, the crossarms being separated vertically

FIG. 2—TYPICAL VOLT-TIME CURVES AND BREAKDOWN CURVES FOR COMPONENT PARTS OF WOOD POLE TOP ASSEMBLIES

*Various lengths of fir crossarm.* The crossarms used were standard creosoted fir arms of 4 by 5 in. cross section which had been used for several years. The electrodes consisted of two metal bands around the crossarm. Fig. 2 shows typical volt-time curves, and breakdown curves for different time lags. It will be noted that there is a wide scattering of points, the extreme points in the volt-time band being nearly 20 per cent from the median curve. These erratic results are explained by the non-homogeneity of the wood and variation in physical characteristics of the different specimens tested, such as moisture, aging and type of grain. Considerable variance was found in tests on a single arm with all external conditions constant.

Investigation of the comparative impulse strengths of wet and dry, freshly creosoted and untreated, new and well seasoned, and of splintered and unscarred arms failed to reveal any measurable trend due to these causes.

*Pole tests.* Some tests made on a section of wood pole alone between electrodes of wire banding showed such a wide variance between individual poles that the tests were not extended, particularly since values are available.[3,6] Impulse tests on a badly checked and weathered chestnut pole showed a sparkover voltage of about 90 kv per ft at 5 microseconds. The impulse spark occurred within the wood fibers and oscillograms showed a slow voltage drop at breakdown, similar to a discharge through a high resistance.

*Sparkover from one conductor to ground over arm.* Breakdown curves for different time lags are shown in Fig. 2. The impulse voltage was applied to an 8-ft rod mounted on an insulator. A grounded band around the arm at various distances from the center line of the insulator formed the other electrode. The volt-time curve shows scattering similar to the crossarm tests. The insulator used on all tests was the standard 45-kv pin type.

*Sparkover from conductor to conductor on the same arm.* Breakdown curves are shown in Fig. 2 for sparkover between conductors mounted on insulators at varying spacings on the same arm. Due to the air breakdown, the original data points show but slight scattering.

*Sparkover between conductors spaced 8 ft on a crossarm with varying lengths of arm short-circuited.* This test was to simulate metal braces of varying lengths. Fig. 3 shows the test arrangement and Fig. 2 gives the breakdown curves.

*Sparkover between conductors separated vertically.* Sparkover between conductors on insulators mounted on crossarms, one vertically above the other, was measured for varying spacings. Breakdown curves are shown in Fig. 2.

Comparison of impulse strength calculated from these curves and actual pole top values show a maximum deviation of 20 per cent and an average of about 10 per cent. Actual conditions on a pole may vary considerably from test conditions, due to gradient distortion by adjacent metal. Fig. 4 shows a comparison of the measured values on a double-armed pole with those estimated from the component part curves. Since the sparkover voltages for double arms are about 7 per cent higher than for single arms, the agreement will, in general, be closer than indicated.

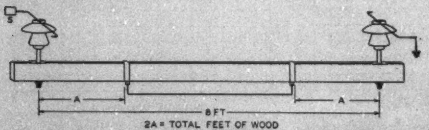


FIG. 3—TEST ARRANGEMENT FOR TWO 45-KV PIN INSULATORS MOUNTED ON A 10-FOOT FIR CROSSARM WITH METAL STRAPS IN CENTER SIMULATING VARIOUS LENGTH CROSSARM BRACES

Wood poles, crossarms, and particularly wooden braces shatter considerably under impulse sparkover. With the available surge current, no appreciable increase in shattering due to bolts or hardware was noticed, although with the high current in lightning strokes, the establishment of multiple paths may cause such an effect. Tests show a lower sparkover voltage through wood fibers than for surface flashover, thus increasing the tendency to splinter. With properly designed gaps, the path of the spark may be confined to the air as shown in Fig. 6. Tests on the gap clearances necessary to protect wood insulation checked Melvin's results.[3] Needle gap spacings to protect given assemblies may be obtained from needle gap curves and the component part curves given in this paper, allowing a reasonable factor of safety.

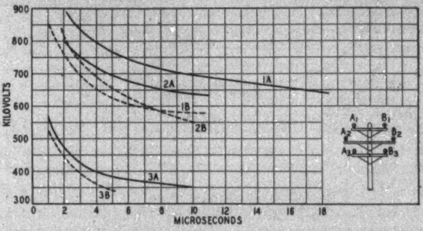


FIG. 4—COMPARISON ACTUAL AND ESTIMATED FLASHOVER CURVES FOR VERTICAL CONFIGURATION POLE WITH DOUBLE ARMS AND METAL BRACES

Curve 1A—-Flashover from phase $A_2$ to phase $B_2$
1B—Same, estimated
2A—Flashover from phase $A_3$ to phase $A_3$
2B—-Same, estimated
3A—-Flashover from phase $A_3$ to phase $B_3$
3B—Same, estimated

It was impractical to make tests covering many combinations of insulation in series. The curves given, while necessarily not complete, will be of chief value in designing for preferred sparkover paths and for comparison of insulation levels.

## TESTS ON STANDARD TYPES OF 26-KV TRANSMISSION WOOD POLE ASSEMBLIES

To check the estimated values of pole top sparkover voltages, several types of straight span, 26-kv transmission poles now in use were constructed and tested. Volt-time curves were determined for flashover between any two conductors and for conductor to grounded guy sparkovers, when within range of the surge generator. As the component part curves were found reasonably accurate for estimating, tests were not made on angle or pothead poles. In all tests 8-ft copper rods simulated the conductors. Only representative values are given as space does not permit inclusion of the complete impulse curves for each sparkover path. Table I gives the dimensions of all standard pole tops tested.

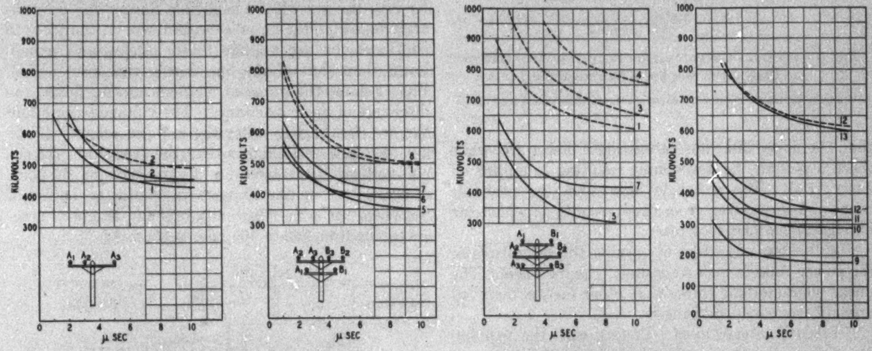
Fig. 5 presents a summary of the results from all pole tops tested. It will be noted that wooden braces on the horizontal configuration pole do not improve the line-to-line insulation. On the triangular configuration pole,

TABLE I—STANDARD 26-KV LINE POLE TOP DIMENSIONS FOR USE WITH FIG. 4

| Configuration | Crossarms | Crossarm vertical spacing | Braces | Conductor spacing in inches $A_1 - B_1$ | $A_2 - B_2$ | $A_3 - B_3$ |
|---|---|---|---|---|---|---|
| Double-circuit Triangular | One 7 ft<br>One 10 ft | 32 in. | Metal—<br>Spread—60 in.<br>Drop—18 in. | 76 | 112 | 40 |
| Double-circuit Vertical | Two 7 ft<br>One 10 ft | 42 in. | Same | 76 | 112 | 76 |
| Single-circuit Horizontal | One 10 ft | | Same | $\left(\frac{A_1 - A_2}{36}\right)$ | $\left(\frac{A_1 - A_2}{76}\right)$ | $\left(\frac{A_1 - A_3}{112}\right)$ |

about 40 per cent increase in line-to-line impulse strength is gained by using wooden braces. Due to the equilateral spacing, nothing can be gained by increased arm separation. Wooden braces on the vertical configuration pole about double the line-to-line insulation. At 60-in. arm spacing the minimum line-to-line insulation becomes as great as can be secured, due to the fixed clearances across the 7-ft arm.

The lowest line-to-ground sparkovers for various guy positions on a pole using standard insulator spacing on a 7-ft arm are also shown in Fig. 5. It can be seen that small porcelain guy insulators add very little insulation and also that guying to the double arm through-bolt is very undesirable. When line stresses permit, the guy should be attached several feet below the bottom brace. When guying to adjacent poles, as great a distance as possible should be left between the point of attachment and any ground.



Curve 1. $A_1$-$A_2$ standard (See Table I)
Curve 2. $A_1$-$A_2$ double arms
Curve 3. $A_1$-$A_2$ arms spaced 48 in.
Curve 4. $A_1$-$A_2$ arms spaced 60 in.
Curve 5. $A_1$-$B_1$ standard (See Table I)
Curve 6. $A_1$-$B_1$ double arms
Curve 7. $A_1$-$B_1$ long-arm brace 60 in. spread, short 48 in.
Curve 8. $A_2$-$A_3$ arms spaced 36 in.
Curve 9. guy to crossarm through bolt
Curve 10. guy to brace: 2 guy insulators
Curve 11. guy to brace: 4 guy insulators
Curve 12. guy between brace and crossarm
Curve 13. typical wood strain guy insulator

FIG. 5—SUMMARY OF MINIMUM LINE-TO-LINE FLASHOVER VOLTAGES FOR VARIATION IN 3 TYPES OF POLE TOPS AND FOR VARIOUS GUY POSITIONS; DOTTED CURVES ARE FOR WOODEN CROSSARM BRACES

## POWER FOLLOW TESTS

To make a comprehensive study of the development of a power arc following an impulse breakdown would require controlling numerous factors among which are:

1. Magnitude of the 60-cycle power voltage.
2. Angle on power voltage at which the impulse breakdown occurs.
3. Length of breakdown path.
4. Magnitude and duration of impulse current.
5. Breakdown through air or solid dielectric.
6. Voltage recovery characteristic at flashover point.
7. Short-circuit current available.

In this investigation, data were sought on factors 1 to 5 inclusive.

Fig. 7 shows the test circuit. The tripping potential could be varied in 30 degree steps leading or lagging the crest voltage of the supply. The short-circuit current at 26.4 kv was limited to 24.2 rms amperes symmetrical current. The voltage was controlled by a regulator in series with the 350 kva, 4,800/30,000-volt transformer. An arrester and inductance protected the transformer winding. The gap electrodes were copperweld rods, ½ inch diameter. Maximum consistency in results was obtained by energizing the master trip gap and then charging the surge generator.

For a given tripping angle, the gap was progressively increased until the maximum distance at which power would follow was reached. Fig. 8 shows the results of several hundred tests at 26.4 kv at gap spacings from 3 to 50 inches. The height of each rectangle indicates the range of variation of the follow distances, those greater than the upper limit not permitting a power arc, while those less than the lower limit resulting in an arc on every trial. The rectangle base gives the probable range of angles, taken from osiso records, at which the impulse breakdown took place.

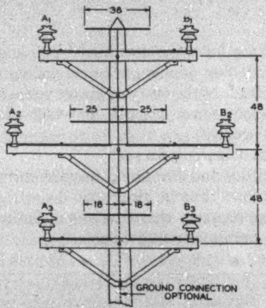


FIG. 6—VERTICAL CONFIGURATION POLE TOP WITH GAP TO PREVENT WOOD FROM SHATTERING

All dimensions in inches: for crossarm and brace dimensions see Table I

Fig. 9 shows the effect of varying the magnitude of the power voltage with a constant tripping angle. The linear characteristic shows that other factors involved probably remained unchanged.

*Breakdown through wood.* Testing with the tripping connections to give maximum air power follow, wood was subjected to breakdown with an air gap in series to prevent continuous application of the a-c voltage to the wood. For surface breakdown, the power follow distance was substantially the same as in the air gap tests. When any part of the breakdown was within the body of the wood for a minimum of 12 inches, power follow was prevented. In many cases a shorter wood path sufficed, but the results were variable for lengths under 12 inches.

The gradient necessary to maintain a discharge in a closely confined path is greater than in open air. The impulse arc is thus quickly deionized and a power arc prevented by confining the discharge within wood fibers. Transmission line inspections have revealed many instances where crossarms and pole sections have been splintered by lightning without resulting outages.

Using various means of confining the impulse breakdown within wood, the effectiveness of wood as a deionizing agent was demonstrated. Thirty discharges of 6,000 amperes between nails driven in the center of a 4 by 4 in. cross section gave no power arc, but shattering increased with smaller cross sections. Trial installations of the wooden block protector are in service and use of them in the future will depend on the operating record obtained. Design details of the blocks will require further field experience, but will probably be similar to those in Fig. 10. Application will be similar to that of the deion protector.

Another deionizing device for use in series with an air gap consisted of a fine wire, over 12 inches long, clamped between two pieces of wood. The breakdown potential is that of the series gap. Later tests with this device connected between phases of a 22-kv line showed a discharge of the line capacitance and restoration of potential without passage of power current. This device has possibilities as a back-up relief gap for substations.

*Interpretation of results.* An impulse breakdown results in a highly ionized path of small cross section. The inductance of the path being negligible, the line capacitance instantly begins to discharge. Load current transfer into the arc will be negligible during and immediately following the impulse breakdown. If the arc is to continue, the arc voltage must become and remain lower than that of the line during this brief period. Fig. 11 shows the transient relations existing during the discharge of line capacitance. The voltage to maintain the arc rises rapidly after the impulse ceases. If the arc voltage $e_a$ rises higher than the instantaneous circuit voltage, $e(t)$, a condition dependent upon the point of breakdown on the 60-cycle wave and the nature of the path, the arc is effectually broken; the entire process taking from 200 to 400 microseconds.[7]

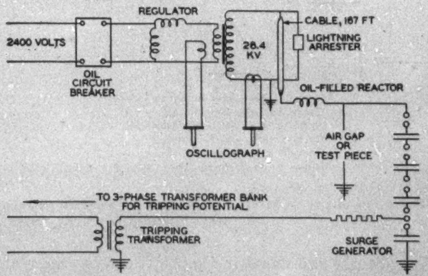


FIG. 7—DIAGRAM OF CIRCUIT USED FOR POWER FOLLOW TEST

If power current flows, it generally follows a transient half cycle which depends on the circuit reactance, the arc voltage and the point of breakdown on the 60-cycle wave. The fate of the arc is decided at the first current zero and conditions at this time depend upon the current transient immediately preceding. The problem is essentially that of the extinction of a long a-c arc in air, discussed by Slepian.[9]

Fig. 12 shows the current transient for impulse breakdown at 30 and 150 degrees on the voltage wave. The instantaneous voltage tending to initiate the arc is the same in each case, but the ensuing current transients differ greatly. $I_1$ has a high maximum and decreases rapidly near zero, while $I_2$ has a low maximum and decreases slowly near zero. At zero for $I_1$ the arc path must withstand a transient recovery voltage of about 2 $e_1$, while, at zero for $I_2$, it must withstand only about 2 $e_2$.

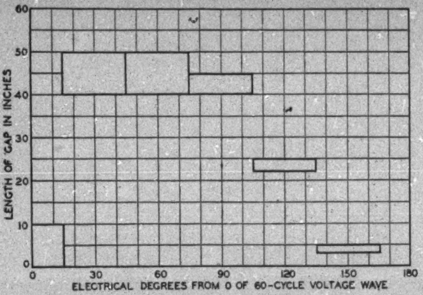


FIG. 8—VARIATION OF POWER FOLLOW DISTANCE WITH POINT ON THE 60-CYCLE VOLTAGE WAVE AT WHICH IMPULSE BREAKDOWN OCCURRED

At current zero, the deionization of a long arc in air may be considered as due to diffusion of ions from the high temperature core of the positive column to the cooler boundary regions surrounding the arc and their subsequent recombination in this region. If this explanation be accepted, a qualitative expression for the breakdown gradient of the arc space after current zero is:

$$X = \frac{B}{a\, n_0} \qquad \epsilon^{\frac{c}{a} t} \tag{1}$$

where $x$ = breakdown gradient in volts per cm
$t$ = time after current zero
$a$ = radius of arc section
$n_o$ = ion density at current zero
$B, c$ = constants

Since the cross sectional area of the arc lags behind the decreasing current, its value at current zero will be greater, the higher the rate of current decrease. It is evident from Fig. 12 that $I_1$ requires a much larger arc section at maximum current than does $I_2$. Near current zero $I_1$ decreases more rapidly than $I_2$. These factors give a much smaller arc section at current zero for $I_2$ than for $I_1$. Equation (1) indicates this variation in arc section is mainly responsible for the variation of $X$.

Thus $I_1$ results in a low arc breakdown gradient and a comparatively high recovery voltage which permits long power arcs after impulse flashover, the opposite being true for $I_2$.

In the region near voltage zero, the power voltage was insufficient to initiate the current flow except for the short spacings noted. Since in these tests no capacitance discharged through the impulse path, the rate of current flow was determined by the difference between the instantaneous arc and circuit voltages immediately following the impulse current, divided by the circuit inductance. Near voltage zero the arc voltage rises above the circuit voltage and the transient current flows only for short gap spacings.

Equation (1) also shows that for the actual transient currents met in practise the arc breakdown gradient curve will have a much lower initial value, and will increase much more slowly than the low transient test current. Therefore, if the conditions necessary for the establishment of the first transient half cycle are fulfilled, the arc in air will not extinguish at the first current zero. Thus the factors determining the occurrence of a power arc following lightning sparkover on a transmission line must be found in the fast transient phenomenon indicated in Fig. 11.

On a transmission line, the discharge of the line capacitance furnishes a current to the arc much greater than the initial test current here described, hence it may easily be seen how very long follow arcs can occur in practise.

A few tests on the effect of low or high impulse current during breakdown revealed no satisfactory definite trend.

## GENERAL DESIGN PRINCIPLES

The data presented can be used to design a pole line which should give adequate lightning performance and meet local operating requirements. The following factors should be considered in the design of new pole lines:

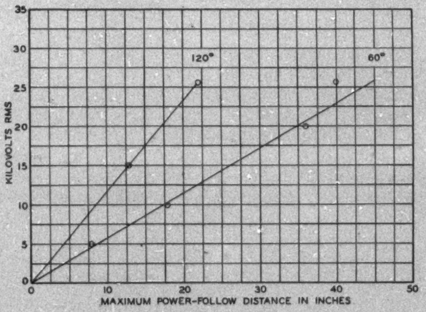


FIG. 9—VARIATION OF FOLLOW DISTANCE WITH POWER VOLTAGE FOR GIVEN PHASE ANGLE

1. When the importance of a line economically justifies it, improved lightning performance may be secured by the judicial use of wood and increased clearances; or application of a dynamic arc suppresser such as the deion fiber tube arrester or a device employing the suppressing

qualities of wood. Some type of protector is indicated as the most efficient method of accomplishing this purpose, since other data show that the prevention of the dynamic follow arc by increased clearances is not to be relied upon.

2. Whichever design is followed, the pole top should be so proportioned that the lightning sparkover will occur through the air, or through the protector rather than through the crossarms or wood braces.

3. When no protectors are used, it will be advisable to make the insulation level of the line as high as possible, and also of uniform insulation between the several types of poles, in order to minimize the number of flashovers. Care, of course, should be taken to provide adequate protection for equipment at the line terminals, and for any intervening cable sections.

4. When the system conditions make a ground fault preferable to one from line to line, it is desirable to make the voltage required for flashover to ground less than that required between lines.

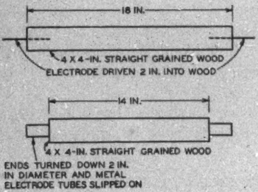

18 IN.
4 X 4-IN. STRAIGHT GRAINED WOOD
ELECTRODE DRIVEN 2 IN. INTO WOOD
14 IN.
4 X 4-IN. STRAIGHT GRAINED WOOD
ENDS TURNED DOWN 2 IN.
IN DIAMETER AND METAL
ELECTRODE TUBES SLIPPED ON

FIG. 10—TWO SUGGESTED FORMS OF WOODEN BLOCK PROTECTORS FOR 26-KV OPERATION

5. In the case of two-circuit lines, it is desirable to have flashovers between circuits take place between the same phases, as then no interruption will result.

One line embodying these principles has been constructed by the Public Service Electric and Gas Company. It uses the deion fiber tube protector, one per phase, on a two-circuit pole line in the vertical configuration. Due to special maintenance requirements the top and bottom crossarms are 10 ft and the middle 14 ft, spaced 4 ft on the pole. The protectors are placed on every fourth pole which has metal crossarm braces, the intervening poles having wooden cross arm braces. Care has been taken to keep the angle pole insulation on a high level and to install protectors on adjacent poles.

## CONCLUSIONS

1. Wood is an effective insulator for lightning voltages and should be fully utilized in transmission line design when increased impulse insulation is desired.

2. The net flashover voltages (one electrode grounded) of wood and porcelain combinations of simple pole tops can be estimated within 20 per cent from the data presented.

3. Seasoned wood has high 60-cycle insulating value for short times of voltage application when dry, but its insulation value is much impaired with even a slight increase in moisture content. Creosoting has no appreciable effect on these properties.

4. Creosoting or moisture has no appreciable effect on the impulse sparkover values for wood.

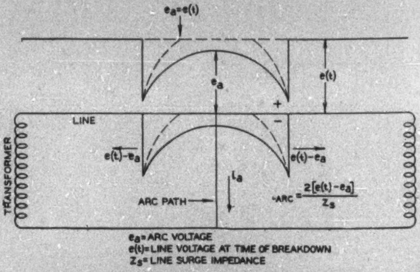

$e_a = e(t)$
$e_a$
$e(t)$
+
−
LINE
TRANSFORMER
$e(t) - e_a$
$e(t) - e_a$
$i_a$
ARC PATH
$i_{ARC} = \frac{2[e(t) - e_a]}{Z_s}$
$e_a$ = ARC VOLTAGE
$e(t)$ = LINE VOLTAGE AT TIME OF BREAKDOWN
$Z_s$ = LINE SURGE IMPEDANCE

FIG. 11—INITIAL FAST TRANSIENT SUPPLYING CURRENT TO THE BREAKDOWN PATH BY DISCHARGE OF THE LINE CAPACITANCE

5. Measurements of 60-cycle arcovers on wood pole tops cannot be used as an accurate indication of the impulse sparkover voltages.

6. Tests indicate that the occurrence of the dynamic arc following sparkover cannot be eliminated by increased clearances within practical design limits, for the operating voltages under consideration.

7. The fact that the dynamic arc was prevented from following the path of an impulse arc when confined within wood fibers offers interesting possibilities for field experiments.

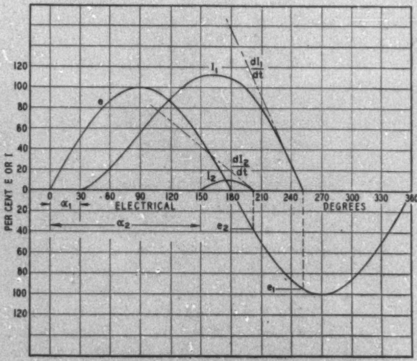


FIG. 12—SLOW TRANSIENT CURRENT THROUGH THE ARC

8. Damage to pole tops by wood splintering can be prevented by application of a suitable gap having a breakdown voltage less than that shown to be required to spark over the insulator and wood.

9. Data are now available for designing a wood pole line with almost any practical degree of lightning reliability, economic considerations being the limiting factor.

### ACKNOWLEDGMENT

The authors wish to express their appreciation to Messrs. A. W. Gothberg and J. J. Torok for their invaluable assistance in planning and carrying out the tests. The suggestions of Messrs. R. N. Conwell, H. K. Sels, L. W. Codding and G. E. Dean, and the field assistance of Mr. E. E. Kussmaul, Mr. F. A. Brownell and the Metuchen Laboratory personnel assisted greatly in this work.

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## Discussion

**H. K. Sels:** At present the more or less definite conclusions stated in the paper are justified by test results only, although mention was made of a line using the deion fiber tube protector and installations of wooden block protectors on the Public Service Electric and Gas Company system. It is the purpose of this discussion to present the interesting features of these installations.

The line is of vertical configuration and, due to special maintenance requirements of keeping 1 circuit in service at all times, has two 10-ft and one 14-ft crossarms, spaced 4 ft apart on the pole as shown in Fig. 1. As the span length is about 100 ft, it is believed that adequate protection will be obtained from protectors installed on every fourth pole which has metal crossarm braces. Protectors are also installed adjacent to poles with potheads, of which there are 4 sets on each circuit, and also next to angle poles. Unprotected poles are unguyed and equipped with wooden crossarm braces giving flashover values, phase to phase, well in excess of 1,000 kv. A large difference in insulation level exists between the poles with protectors flashing over at about 200 kv to ground and the intermediate pole insulation which is in excess of 1,000 kv. An effort was made to have all of the driven ground resistances less than 20 ohms and those adjacent to pothead and angle poles less than 2 ohms. Megger readings after installation showed that all resistances were less than 17 ohms and 85 per cent less than 8 ohms.

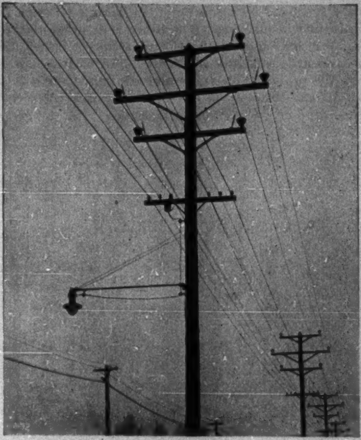

FIG. 1—PROTECTED POLE USING DEION FIBER TUBE PROTECTORS AND METAL CROSSARM BRACES

Second pole unprotected with wooden crossarm braces

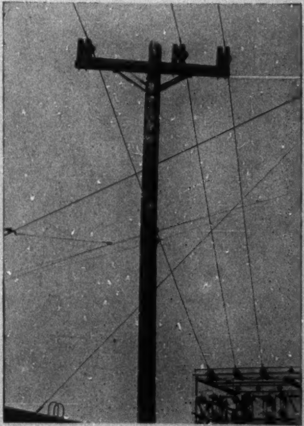

FIG. 2—PROTECTED TERMINAL POLE USING WOODEN BLOCK PROTECTORS WITH PIN ELECTRODES

In order to provide some measure of lightning protection for two small outdoor substations, each fed by two incoming lines, 4 installations of the wooden block protectors have been made. These protectors were installed on each pole nearest the substation, one installation similar to each type shown in Fig. 10 of the paper being used at each substation. The wooden blocks with the pins in the end are mounted on a separate crossarm under the line conductors, double blocks being used in case one should be shattered by a nearby direct lightning stroke. Fig. 2 illustrates this installation. The other type of protector with turned down ends and tubular electrodes was mounted directly on the crossarm with the conductors. In each case the gap between the protector electrode and the conductor is 3 inches and the distance through the wood is 9 inches. The wood is untreated fir, 5 in. by 5 in. in cross section. The lower end of the protectors was connected to a driven ground and a 50 ft to 75 ft tie to the substation ground which is under 2 ohms resistance. The value of impulse current to which the protectors will be subjected is limited by the line insulation and will be less than the 6,000 amperes at which the blocks have been tested without appreciable shattering. This is believed to be adequate to protect the substation bus which is insulated to the 34.5-kv voltage class, without any appreciable effect on the line operation.

Unfortunately, all this work was completed so late in the 1932 lightning season that no operating results were obtained but it is hoped that these installations, together with others, will ultimately justify the conclusions drawn from the tests and presented in the paper.

# Operating Experience With Wood Utilized As Lightning Insulation

BY H. L. MELVIN*
Fellow, A.I.E.E.

**Synopsis.**—*Operating experience with a large number of lines of various types, utilizing wood as lightning insulation, has demonstrated that ordinary woods have considerable insulation strength for lightning voltages, and that wood can be used to advantage in combination with other measures for improving the lightning performance of lines. The analyses have contributed materially to the present general conclusion that lightning strokes terminating on conductors and structures are responsible for the majority of lightning flashovers, at least on the higher-voltage lines; also that direct strokes must and can be coped with. The methods offering the greatest promise at present are; (1) diverting the lightning strokes from the conductors and conducting the lightning currents to earth without permitting flashover to the power conductors; (2) draining the lightning from the power conductors through fast operating dynamic follow current interrupting devices, thus avoiding insulator flashovers; and (3), a combination of these two methods.*

*High lightning insulations alone are not generally effective in reducing the number of lightning tripouts of lines, though in the lower-voltage ranges, some decrease in the probability of dynamic current following the lightning arcs may be realized.*

## INTRODUCTION

WITH the active initiation of lightning investigations a few years ago, the importance of having data on the impulse characteristics of insulations, and of a better understanding of the use of insulations available in construction, came to the fore. Wood had long been recognized as having insulating properties, indicated by application in line construction, use in the manufacture of apparatus, and from laboratory tests. To obtain measures of the impulse strengths of various amounts and kinds of woods as they might be used in line construction, and under varying conditions of contamination and moisture, a series of tests were conducted early in 1928 which were presented to the Institute by the author at the Pacific Coast Convention in 1929.[1] The results of these tests held considerable interest, inasmuch as relatively high insulation strengths were indicated for lightning voltages for practically all of the ordinary kinds of woods, under practically all expected service conditions. It also was indicated that wood could be protected from damage by the use of bypass protecting air gaps. Furthermore, it seemed practicable to materially increase the lightning insulation strengths of wood lines by rather simple and inexpensive methods. Accordingly, ideas developed from these data were applied in an experimental manner in the construction of a number of lines, to determine from actual experience what service improvements might be realized, and for the purpose of contributing to the lightning research results.

These transmission lines under trial, totaling approximately 1,300 miles and located on several systems, are representative of most of the severe lightning conditions to be met with in the United States. Space does not permit nor would interest justify describing and tabulating the results in detail. It is believed, therefore, that it will suffice to show several typical illustrations with brief descriptions of the construction and present only the more important results and the pertinent conclusions drawn from the carefully collected data and observations. With knowledge concerning the mechanism and magnitudes of lightning still incomplete, it is of course impracticable to make the statements very positive or final.

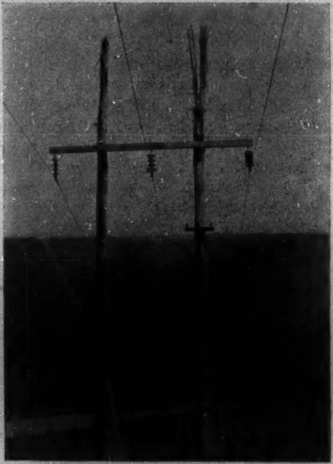

FIG. 1—LIGHTNING DAMAGE TO UNPROTECTED WOOD STRUCTURE
(Photographed after temporary repairs)

## DESCRIPTION OF EXPERIMENTAL CONSTRUCTION

When it is considered that lightning voltages are of sufficient magnitude to break down great distances through air, and strokes terminating on wood structures will do damage as illustrated by Figs. 1 and 2, little hope

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*Electrical Engineer, Electric Bond and Share Co., New York, N. Y.

1. For references see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

can be entertained of stopping lightning with insulation alone. However, it was thought that possibly some lightning of lesser voltage and current magnitudes (including induced voltages of 50 to 75 kv per ft of conductor height and possibly mild branch strokes) might appear on lines and be held with high insulation, thus reducing line tripouts.

FIG. 2—BASE OF FIG. 1 STRUCTURE

The first trials consisted of simply increasing the insulation of the three phases to ground by substantial amounts. Fig. 3 illustrates a 66-kv line of the Kansas Gas and Electric Company, with 9-ft guy insulators and 3-ft 8-in. protecting gaps in multiple to ground, mounted on the pole. Initially, unprotected 7-ft gaps between bands wrapped around the poles were used on all structures, similar to those illustrated in Fig. 7. Pole gap damage was so severe, however, that the protecting horn gaps were later added across 10-ft pole gaps. Frequently from three to six consecutive poles were flashed by what was probably a single lightning discharge. Surge voltage recorders were connected to this section of line for one and one-half seasons before, and three and one-half seasons after, the guy insulators were installed.

Two 66-kv lines of the Pennsylvania Power & Light Company were equipped with 9-ft wood guy insulators with protecting horn gaps mounted on the insulators. About one-third of the guy insulators were of the type illustrated by Fig. 6 with protecting gaps of 6 ft 6 in. and the others were similar to those shown in Fig. 3 with 3-ft 7-in. protecting gaps. Surge voltage recorders were connected to a line of similar construction except for the guy insulators for two seasons and to one of these lines for one season.

Several H-frame, 110-kv lines of the Arkansas Power & Light Company, Louisiana Power & Light Company, Mississippi Power & Light Company, Carolina Power & Light Company, Tennessee Public Service Company and the Compania Nacional de Electricidad, Mexico, also some 66-kv construction of the Carolina Power & Light Company, employed 18-ft to 24-ft guy insulators. Figs. 4, 7 and 10 are illustrative of the construction. Protection for the guy insulators on all of these lines was provided by gaps mounted on the poles.

On the first line with two 9-ft guy insulators in series, a pole gap was used of 13 ft 6 in. between bands wrapped around the poles, as shown by Fig. 7. On all subsequent construction, protecting horn gaps were applied. For the lines employing two 9-ft or one 18-ft insulator the protecting gaps were 7 ft 2 in. across 20 ft of pole, with a clearance of 3 ft 6 in. between the tips of the horns and the wood. On a line with two 12-ft guy insulators, the protecting gaps were 9 ft 3 in. across 26 ft of pole with a clearance to the horn tips of 4 ft 6 in.

Guy insulator and pole gap protection has been accomplished with the above protecting gap dimensions in a very high percentage of the cases. On the 50-mile line of the Tennessee Public Service Company with two 12-ft guy insulators, where some damage was experienced, the guy anchor rods were connected to the pole butt grounds, also, one-half of the gaps were shortened to 8 ft and one-half to 7 ft. On a line of the Louisiana Power & Light Company with 18-ft guy insulators, the protecting gaps were shortened to 5 ft 9 in. These changes have practically prevented further damage.

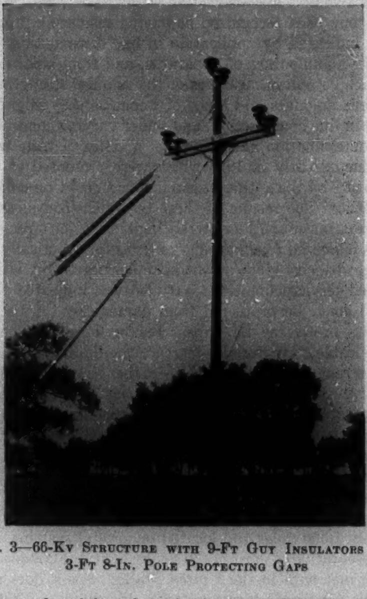

FIG. 3—66-KV STRUCTURE WITH 9-FT GUY INSULATORS AND 3-FT 8-IN. POLE PROTECTING GAPS

The use of the crossarm insulation varied. On some lines the entire length was employed in order to maintain the maximum possible phase-to-phase insulation as well as to ground; on others only the end sections were bonded to the top of the protecting gaps; and in some cases, the entire arm was bonded to prevent crossarm damage.

On about one-third of the lines, the unguyed structures utilized the full pole and crossarm insulation; on another third, the amount of wood utilized was about the same on all structures and protection was provided initially for the wood; and on the balance, provision was made for the future installation of pole protecting gaps.

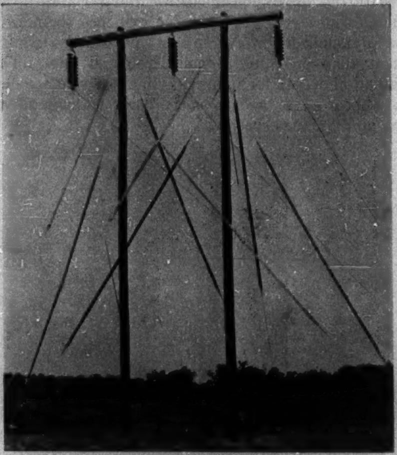

Fig. 4—110-Kv Structure with Two 12-Ft Guy Insulators and 8-Ft Pole Protecting Gaps

Other wood lines made full use of the crossarms, and adequate clearances were maintained between conductors and guys, also guy insulators were employed to a limited extent. On one of these lines on the Texas Power & Light Company system, operating at 132 kv, surge voltage recorders were connected for two seasons.

Another application of protecting gaps is illustrated by Fig. 5. Several lines on the systems of the Texas Power & Light Company and Texas Electric Service Company with conventional overhead ground wires were so equipped to utilize the insulation of the crossarm and at the same time protect them from damage by those lightning strokes which are not diverted successfully.

Figs. 8, 9 and 10 are illustrations of the so-called drainage scheme, described in a paper presented by Messrs. Pittman and Torok in 1930.[2] Here the crossarm insulation is used to provide the margin necessary for directing the lightning flashes through the dynamic follow current interrupting devices.[1] Wood guy insulators were used in the design of particular structures. It might be added that if experience indicates the probability of lightning strokes to the ends of the crossarms with resultant damage, pole bayonets sufficiently high to intercept the strokes may be advisable.

Three 110-kv lines of this design are in operation on the Arkansas Power & Light Company system and a section of 110-kv line on the Tennessee Public Service Company system. Also a very limited application of dynamic current interrupting devices has been made on distribution lines.

In the lightning diversion design illustrated by Figs. 11 and 12 the full insulation of the crossarm is utilized, also, guy insulators were employed with certain structures. The following features in connection with this 70-mile, 132-kv line of the Texas Power & Light Company may be of interest; normal span length 550 ft; approximate clearance between diverting cables and conductors at midspan 20 ft; steel lightning diverting cables bonded together at top of structure; pole butt grounds bonded together by buried wire at base; lightning insulation of nine suspension units plus 7 ft of crossarm, equivalent to about sixteen units; ground resistance values per structure (two pole butts in parallel) 40 per cent below 25 ohms, 40 per cent between 25 and 100 ohms and the balance above 100 ohms.

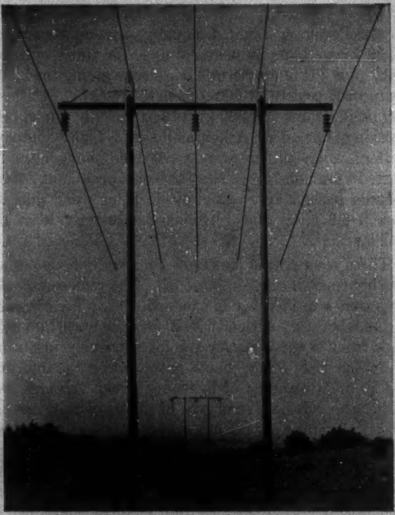

Fig. 5—66-Kv Structure with Conventional Overhead Ground Wires and Crossarm Protecting Gaps

Another use of wood in the application of lightning diverting cables is on the Wallenpaupack-Siegfried 220-kv line of the Pennsylvania Power & Light Company.[4] The diverting cables are supported by wood poles mounted on top of the steel towers and grounded through the medium of the system of guys. With this design the poles provide the insulation to prevent the lightning current from being conducted through the tower.

## OPERATING RESULTS

Surge voltage recorders on the 66-kv lines of the Kansas Gas and Electric Company and Pennsylvania Power & Light Company utilizing the equivalent of about 7 ft of wood in series with 70-kv rated pin type insulators, yielded several records of 1,000 kv to in excess of 1,800 kv. The higher value represented the recorder limit with the potentiometer ratio used, and this voltage was recorded seven times for lightning flashovers on the line ¼ to 1½ miles away from the instruments. Maximum records of approximately 600 kv were obtained for an insulator plus about 1 ft of pole or 2 ft of crossarm. Likewise on the 132-kv line of the Texas Power & Light Company, several records of 1,000 kv to 2,200 kv were obtained for nine suspension units plus 7 ft of crossarm. The stroke giving the 2,200-kv record, occurred 7,500 ft from the recorder. Cathode ray oscillograms of 4,500 kv and 5,000 kv obtained on a section of line on the Arkansas Power & Light Company system where all guys were removed, have been reported previously.[3] The strokes producing these records flashed approximately 45 ft of wood and occurred 2.3 miles and 4.0 miles respectively from the oscillograph.

These records provide ample confirmation that wood has lightning insulation strength. The maximum voltages were considerably in excess of the values obtained in the laboratory with the ¼-20 impulse wave and indicate front-of-wave flashovers for extremely fast rates of voltage rise. They should not, however, be interpreted as measurements of lightning stroke voltages, but rather the lightning strengths of the insulations, as are practically all other records which have been obtained in a similar manner. A speculation of possible interest is that if a linear relation between insulation strength and pole length holds, the voltages which could be measured across a wood structure of ordinary height would be in the order of 12,000 kv to 15,000 kv.

Few surge records of lightning voltages were obtained in the band between the flashover of ordinary line insulators and the high lightning insulations developed by the use of wood guy insulators. Also, line tripouts were coincident with practically all the high records. This indicated that few lightning voltages appeared on the lines which were not of sufficient magnitude to cause flashover. In many instances relatively low readings were obtained on some of the instruments accompanying line tripout, because in general only attenuated values were recorded on account of the spacing of the instruments.

The carefully analyzed tripout records for a number of lines equipped with long wood guy insulators and lightning flashover strengths of 1,500-kv to 3,500-kv compared with otherwise similarly constructed lines but with less than one-half of these insulation strengths, have not indicated any appreciable decrease in the number of tripouts with the higher insulation.

With the longer guy insulators and lower operating voltages however, there is some evidence to indicate that dynamic follow current may be slightly less frequent than on conventionally insulated lines. This method of attack for improving line performance does not appear advantageous as compared with the diversion and drainage schemes.

FIG. 6—DAMAGED 9-FT GUY INSULATOR WITH 6-FT 6-IN. PROTECTING GAPS

High lightning insulation in combination with lightning diversion cables properly located and grounded, somewhat as illustrated by Figs. 11 and 12, is proving very effective. The 132-kv, 70-mile Texas Power & Light Company line has not tripped out in one year of operation. There is little doubt that it has been exposed to lightning, as storms are prevalent, and a conventional 66-kv line of about the same length, in the same locality, and paralleling it for part of the distance, has been interrupted 26 times due to lightning in the same period. This should not be interpreted as a statement that the line is immune to lightning flashover, as the right strokes may not have occurred at the right points; however, the performance indicates progress and possibilities.

Records indicate two or possibly three direct strokes in two and one-half seasons to the experimental lightning diverting cable installation without line tripout on the Wallenpaupack-Siegfried 220-kv line of the Pennsylvania Power and Light Company.

The utilization of the crossarm insulation in combination with conventional overhead ground wires as illustrated by Fig. 5 is also proving effective though other design features are essential for accomplishing best results in the diversion of lightning strokes.

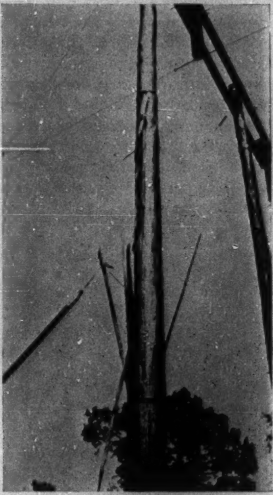

Fig. 7—Damage to 13-Ft 6-In. Unprotected Pole Gap with 18-Ft Guy Insulators

The drainage scheme likewise is showing considerable promise. Records from the three 110-kv lines of the Arkansas Power & Light Company are as follows: The 60-mile line with drain points at each structure has tripped out four times in approximately one year, three of which could be traced to failure of the arc interrupting devices or their mounting, both of which were distinctly in the development stage when installed. The 45-mile line with drain points spaced approximately one-half mile apart, and with no crossarm bonding or pole grounding wires on intermediate structures, has tripped six times in about two-thirds of a lightning season, for which failure of the devices as above can be held almost entirely accountable. With this spacing both the lightning current discharges and dynamic follow current are concentrated through one or two devices. The duties imposed on this line have been found to exceed the capacities of the devices as originally installed. The third line of 28 miles is the one on which the first experiments were conducted[2]. Drain points were spaced about 2 miles initially and then decreased to 1-mile intervals and then to ½-mile on two-thirds of the line. Its record for 2½ years since the shorter separations have been in service has been exceptionally good, only two interruptions occurring due to lightning on the drained sections.

The performance of lines on the same system with comparable construction, except for the application of the arc interrupting devices, has averaged 25 tripouts per 100 miles per year during the same periods. This would give an expected number of tripouts of 15, 11 and 5 respectively for the three lines for one season. Careful examination at the middle of the 1932 lightning season of the telltale devices employed on the 60-mile line indicated 7 successful operations of the drainage scheme.

Protection of the wood when used as lightning insulation has been accomplished very successfully and the following ratios and dimensions appear to be satisfactory for practical application.

Protecting horn gaps mounted on guy insulators or poles should have a ratio of *air gap length* to *clear wood length* of 0.35, and a ratio of *clearance from horn tip to wood* to *clear wood length* of 0.20.

Guy insulator protecting gaps mounted on the poles should span a section of pole equal to or greater than the clear wood in the guy insulators, have the same clearance ratio as above and have a ratio of *air gap length* to *clear wood guy insulator length* of 0.30.

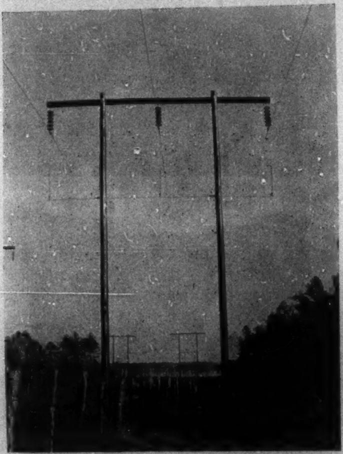

Fig. 8—110-Kv Unguyed Structure with Arc Interrupters

The uncertainties of voltage distribution with different combinations of insulators and crossarms complicate the problem of crossarm protection. Data are not sufficiently complete for offering general ratios. This much has been learned, however, from experience on about

250 miles of line for most of two lightning seasons; that with five suspension units plus 4 ft of clear crossarm with a ratio of *air gap* to *wood length* of 0.38, one arm has been damaged; similarly with five suspension units and 6 ft 6 in. of crossarm and a ratio of 0.33, one crossarm has been damaged.

On lines with conventional overhead ground wires, damage to unprotected crossarms is not generally severe. This probably is accounted for by the ground wires usually intercepting and carrying the major portion of the lightning current even though the flash may also contact the conductors in the span or at the structures.

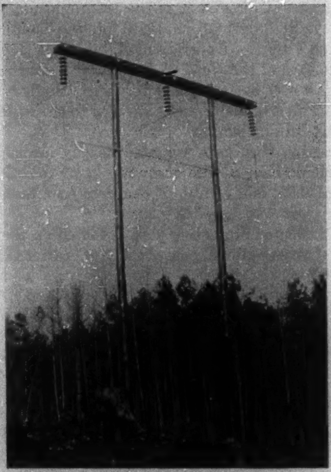

FIG. 9—110-KV GUYED STRUCTURE WITH ARC INTERRUPTERS

Sections of the wood in crossarms frequently can be used to advantage to minimize insulator damage and at the same time increase impulse insulation strengths without unduly exposing the wood to lightning damage. For years this practise has been followed, unintentionally in many instances, however improvements are possible through the proper proportioning of the crossarm wood in series with the insulators so that lightning flashes and dynamic follow current generally will not occur directly across the insulators and wood.

With the high lightning insulations obtained through the use of wood, substation protection usually is imperative. This has been accomplished quite effectively by the use of spillway gaps at the line entrances, with settings for lightning flashover at some margin below the insulation level of the station equipment and buses. These settings, types of gaps and their locations are still in an experimental stage of application, inasmuch as experience and laboratory data, as well as the determinations of insulation level requirements are not complete.

## CONCLUSIONS

Only the more important conclusions, which are considered sufficiently well substantiated for practical application in the utilization of wood as lightning insulation, are outlined. They are drawn from a large amount of experience data and results from surge voltage investigations on specially designed wood lines as well as of conventional construction, accumulated on a number of representative transmission systems operating in severe lightning territories. Further it is believed they represent the summarized thought of the engineers responsible for conducting these coordinated investigations as well as that of the manufacturing company engineers who have participated in reviews of the data during the past few years.

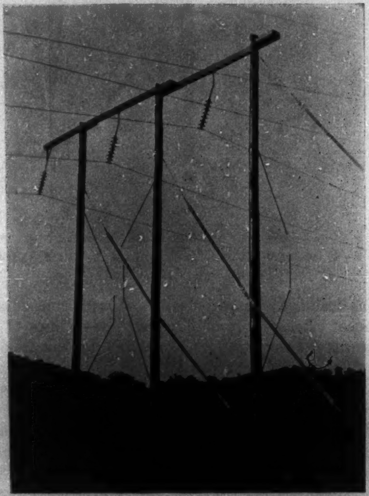

FIG. 10—110-KV ANGLE STRUCTURE WITH ARC INTERRUPTERS

1. High lightning insulation in itself, such as is practicable by utilizing wood guy insulators, poles and crossarms is not effective in materially reducing the number of lightning flashovers occurring on transmission lines.
2. The three general types of design for lines to minimize lightning influence, which at present seem most adaptable and in which the lightning insulation strength of wood can be employed to advantage, are:

a. Diversion of lightning strokes from the power conductors without permitting insulator flashover. This type of design as now conceived requires for successful operation, liberal physical dimensions and insulations as well as favorable grounding conditions, which in general make it more applicable to the higher voltage ratings. More complete data concerning the characteristics of lightning and the constants of the conducting circuits as well as the development of technique for handling the problems involved are required in order to place this method of design on better engineering and economic bases.

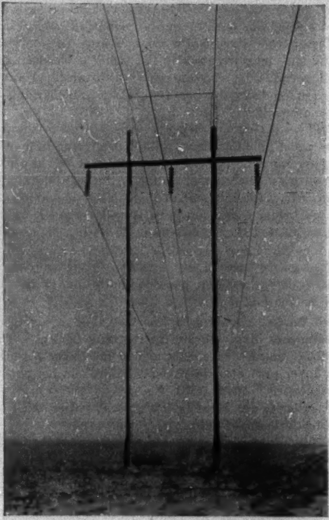

FIG. 11—132-KV STRUCTURE WITH LIGHTNING DIVERTING CABLES

b. The drainage of lightning strokes through dynamic follow current interrupting devices. This method gives promise of proving applicable and advantageous for many situations, particularly in the lower voltage ranges, also where conditions both physical and economic are not favorable for the diversion design. Its success, of course, is very dependent upon the development and limitations of the arc interrupting devices.

c. The simple design in which no particular attempt is made to avoid lightning flashover. Damage to insulators, conductors and structures can be minimized through improved design features for the line, switching and relaying, giving practical assurance that the line will return immediately to service after flashover.

3. The impulse sparkover curves presented in the earlier paper[1] can be used with a reasonable degree of confidence in estimating the comparative lightning insulation strengths of wood, combinations of insulators and wood, insulators and air gaps.

4. Caution must be observed to avoid wood burning from leakage currents, particularly where insulator contamination may occur, and in many instances such conditions may make it impracticable to utilize wood as insulation.

## ACKNOWLEDGMENTS

The cooperative and coordinated application of laboratory test and operating experience data; the systematic collection and careful analysis of line performance data; conclusions drawn therefrom; permission to review the newer resulting developments; and the material supplied specifically for this paper by the engineers who are cooperating in this practical attack upon the lightning problem, are all very much appreciated. The author wishes particularly to thank the engineers of the Arkansas Power & Light Company, Kansas Gas and Electric Company, Texas Power & Light Company, Carolina Power & Light Company, Tennessee Public Service Company, Pennsylvania Power & Light Company, Texas Electric Service Company, Louisiana Power & Light Company and Compania Nacional de Electricidad, Mexico, as well as associates in Electric Bond and Share Company. In many instances the

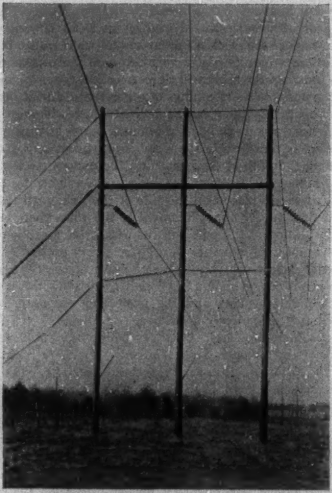

FIG. 12—132-KV ANGLE STRUCTURE WITH LIGHTNING DIVERTING CABLES GROUNDED BY A GUY

experience data from individual systems would merit separate treatment and it is regretted that only a composite summary could be presented in this paper.

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## Discussion

**A. O. Austin:** At first glance it would appear that the performance of systems making use of wood may be more or less erratic. However, it would seem that this may materially be improved as we gain more information or apply a more careful analysis to the results of operation. More and more wood transmission lines are being installed in which the performance is practically 100 per cent. However, in these lines it will be found that there are certain fundamentals which must be given consideration. Work upon a reliability or performance index tends to show up the relative value of certain types of construction or the possible shortcomings of other types, and it is certain that if an operating index can be devised which will show up the various factors, wood can be used to much better advantage.

The effect of moisture in the wood is of utmost importance in determining the path of discharge and the damage to the wood. This has been clearly recognized by many as lightning rods or shunting wires are placed on the side of the pole until the poles have had time to dry out. Removal of the wires then develops the full insulation of the pole and the shattering may be negligible. The amount of moisture and the necessary protection to the wood varies considerably in different parts of the country and must be given consideration. At higher altitudes the moisture content generally is less and the protecting air path weaker, which reduces the tendency to shatter.

Where sufficiently high flashover voltage is obtained the resistance of the air path has a tendency to recover rapidly and prevent the follow-up of normal frequency currents. The use of the wood makes it possible to obtain exceedingly high flashover values as well as abnormally long discharge paths even for low voltage lines, the elimination of which should carefully be guarded against. This can best be accomplished by simple structures.

A direct hit to a transmission conductor certainly is going to cause a flashover if dependence is placed only upon the sizes of insulators commonly used. However, if the length of the arc could be made sufficiently long, the follow-up of normal frequency current can be prevented and the line will not be tripped out.

A high ground resistance or a high impedance in the transmission line or in the neutral will limit the current tending to follow an electrostatic discharge from a direct hit so that the normal frequency may be shut off. A high ground resistance is not necessarily a disadvantage in a wood pole line which makes use of the insulating value of the wood, but unfortunately a high ground resistance generally goes with a low ground capacitance so that the effective height and exposure of the transmission line is increased. However a high ground resistance or low ground capacitance generally is a serious limitation to ground wire protection, hence the use of ground wires which materially reduce the insulation of the wood may seriously increase the tripouts in some sections.

While wood is very valuable in increasing the effective arcing voltage between conductor and ground and in eliminating trouble from birds, it is subject to shattering and burning. The protecting gap can be used to prevent shattering but it is believed that improved methods of impregnation will make it possible to reduce the gap protection materially with the result that increased flashover voltage may be obtained. Multiple wood members rather than single members of large section may so reduce the hazard from shattering that it is possible to develop the full effective length of the cross arm without protection. The increased cost of this construction apparently is well warranted. The same applies to the use of wood cross arms on steel towers.

Burning may be prevented by the use of a bleeder resistance which will permit taking advantage o f the insulation provided by wood even in fog districts where the leakage and charging current of the insulator is high.

It would seem that operating records will go to show that a successful wood pole line may be built in several different ways, but the best operating systems generally will be simple in construction with the effective insulation of the wood developed to a maximum. The development of high flashover values and the limiting of normal frequency current will do much to prevent tripouts, as most disturbances originate with a single phase to ground.

Records such as those shown by Mr. Melvin are exceedingly valuable as they show the possible limitations with different types of construction.

**Edward Beck:** Mr. Melvin has described experience with drainage schemes involving arc interrupting devices. The text indicates that the devices mentioned in the paper resemble the deion flashover protector described by Torok in his paper (No. 31-9) presented in January, 1931.

The experience, described in the present paper, with the arc interrupting devices is as follows:

1. On a 60-mile line with drain points on each structure a total of four outages occurred in one year, three of which the author ascribes to the protectors themselves.
2. On a 45-mile line with drain points separated one-half mile, six outages have occurred in two-thirds of a lightning season, all of which are ascribed to the protectors.
3. On a 28-mile line the performance has been good. The author does not specially attribute either of the two outages which occurred in two and one-half years to the protectors.

Were the outages produced by the protector as a result of failure to clear the circuit after being discharged by lightning or did they originate tripouts themselves without lightning as the primary cause?

Considering (1) and (2) together, it appears that in a total of 10 outages, 9 are laid to the protectors. This might lead the casual reader to reserve judgment on the usefulness of this principle of protection. However, experience with the deion protector invented by Torok and developed by the Westinghouse Company has definitely proved that a relatively wide field for it exists and that in this field it is highly useful. In the first stages of the development of Torok's invention it became evident that the application of the device would not be as simple or as universal as the application of the well known lightning arrester. It became evident also that if design data were carefully established and the protectors constructed in accordance with it, they would find a wide application and that in their field they could be applied with assurance. This requires careful design, construction, and application based on system conditions. Deion flashover protectors have been manufactured for several years and as a result of the painstaking development work it is possible either to pronounce an application unsuitable or to apply them with confidence. Consequently the operating experience with these deion protectors has been good.

To illustrate the importance of careful application; in a certain installation of deion protectors some protector failures occurred. It was subsequently found that the currents to be interrupted were higher than those originally considered. Other installations of deion protectors have given satisfactory operating results. This is no doubt the result of careful development, design, construction and application.

The application of deion protectors was reduced to an engineering basis early in the development. It has been entirely feasible to decide that an application is suitable or unsuitable. If it is suitable the application of the device may be made with good results. Field experience with deion protectors substantiates this. If protector failures occur early in their life, they are attributable either to weakness in the design of construction or to misapplication.

**O. S. Hockaday:** While somewhat aside from the main theme of this paper, the following operating experience may be of interest:

Mr. Melvin points out that while the utilization of wood insulation in itself may not materially decrease line tripouts from lightning, there is some evidence to indicate that the dynamic follow current will be reduced.

On a Texas system of moderate capacity, 200 miles of 66-kv wood H-frame suspension type construction was put into operation late in 1927, no particular advantage being taken of the wood as insulation. During the following two years it was necessary to charge out an average of 60 insulator disks per year on account of burning from flashovers. In an effort to reduce lightning tripouts, the construction was then modified to utilize as much as possible the wood in the structures. Although lightning was about as severe during the two years which followed, the number of replacements dropped to an average of six. Burning of conductors was also reduced to some extent.

During the spring and summer, the transmission system just referred to is badly infested with ravens. These have been responsible in times past for a good many outages. On some lines tripouts from this cause were as frequent as those from lightning. On a particular 66-kv line of pin type construction, 61 miles in length, 42 tripouts occurred within a year which were attributed to these ravens. Gaps were installed in the pole ground wires in 1930 and since that time no tripouts whatsoever have occurred which were known to have been caused by the birds.

These instances substantiate Mr. Melvin's observation that utilization of the wood insulation has advantages other than those from the standpoint of lightning.

**H. L. Melvin:** In Mr. Austin's discussion he suggests the possibility of providing arcing distances of sufficient length to prevent the follow of dynamic current. Operating experience with high voltage lines of conventional construction, and even those employing long guy insulators as described in the paper, the tests made by Brookes, Southgate and Whitehead, also experience on lower voltage lines, do not indicate this type of design as a very practical method for attacking the lightning interruption problem. In the lower voltage ranges, such a design might be feasible but it has the serious objection of raising the lightning insulation strength of the lines to values considerably in excess of terminal equipment and apparatus. Furthermore, with such equipment installed at rather frequent intervals on the lower voltage lines, lightning flashover with dynamic follow-up still would be expected at these points.

The treatment of wood, no doubt, has considerable merit particularly if its life is extended, its mechanical strength under weather conditions improved, and if its lightning insulating strengths are increased and made more uniform. If the wood is exposed to frequent direct lightning discharges, it is the opinion of the author that it should be protected from damage whether treated or not.

Referring to Mr. Beck's discussion the arc interrupters, originally installed on the lines of the Arkansas Power & Light Company, were made up locally by Mr. Pittman from expulsion fuse tubes. Later a few deion tubes, as described in the paper by Mr. Torok were installed. The arc interrupters installed on the two additional lines also were of an experimental design using conventional expulsion fuse tubes. It might be added that the arc interrupter, deion flashover protector, and the expulsion protective gap, are all devices for interrupting the dynamic follow current.

Answering the questions raised regarding line performance, the tripouts which occurred on the lines employing the drainage scheme, were due to flashovers at structures not equipped with arc interrupters or to electrical and mechanical failures of the interrupters. As stated, the tube failures were not entirely unexpected as they were of an experimental design and their interrupting capacities as well as the methods of mounting had not been carefully worked out.

The manner in which wood has been used to minimize flashovers, as described by Mr. Hockaday, is of interest and very important. Good overall performance of lines should be the objective, and to accomplish this, the design must take into account all the elements adversely affecting operation, mechanically and electrically.

It is desired to emphasize that the lightning and short time 60-cycle insulation strength of wood can be utilized to advantage in practically all types of line construction and voltage classes. It is of particular value in combination with properly installed overhead ground wires or dynamic follow current interrupting devices, or for controlling arcing paths to minimize insulator damage. Very high insulation alone to lightning voltages, such as can be obtained through the use of long wood guy insulators and poles, has not proved effective for materially reducing lightning flashovers. The extensive application of this type of construction on the several transmission systems, largely in an experimental manner, has been a valuable supplement to other investigations. The experience has assisted materially in demonstrating that lightning discharges contacting conductors and structures must and can be coped with if line performance is to be substantially improved.

# Light Sensitive Process Control

BY J. V. ALFRIEND, JR.*
Non-member

IN order to keep certain electrochemical processes functioning within tolerable limits without suitable automatic control, it has been necessary, in some cases, to resort to close supervision by chemists who regularly sample the process liquors, determine their concentration and take what corrective measures are indicated. This work can be accomplished by a skilled laborer under the direction of the chemist if there is only one variable and if this variable is responsive to colormetric analysis either by the addition of an indicator or by its own color or opacity.

However, even this is expensive, slow, and inaccurate. The accuracy in the best of cases will vary with the health and fatigue of the analyst, with the conditions of illumination, and with the pressure of other work. Furthermore the analyst must change the speeds of pumps, conveyers, compressors, etc., and either hope that the correction is sufficient or waste valuable time waiting for the correction to take effect before he can obtain a check sample.

Recent developments in the matching of colors, the measurement of the intensity of smoke, and the automatic control of illumination indicated that colormetric process control might be obtained automatically by some modification of this new equipment which has proved commercially successful. Therefore a study was made covering the variables encountered in process control that should affect a light sensitive device similar to those just mentioned. The following list† gives a few applications where automatic control is definitely advantageous and where the variable chemical affects the shade or opacity of a liquor either directly, or indirectly by the addition of an indicator.

In metal flotation the maximum recovery is possible over a very narrow range of hydrogen ion concentration. The addition of an indicator to a filtered sample is required to bring out the definite shade corresponding to the concentration. Both the filtration and the addition of indicator can, of course, be made automatic. The lime feed can then be controlled for a definite hydrogen ion concentration at the launder or in the flotation tanks.

In electrolytic reduction plants, close control must be exercised over the acid concentration of fresh electrolyte from the leaching vats, and the spent electrolyte from the electrolytic tanks in conjunction with the flow of make up acid if required by the process. The acidity of the waste liquors should at least be indicated and preferably regulated. Determination of hydrogen ion concentration by colormetric methods and the control of pump speeds and electrolytic current flow will maintain the desired balance and give the necessary indications.

In electrolytic refining the best power efficiency is obtained at a definite hydrogen ion concentration, which is steadily reduced as the electrolyte increases in copper content. Control of this concentration by colormetric methods affecting the speeds of the circulation pumps and the current flow in the stripping tanks will maintain the desired acidity.

Numerous other applications in the electrochemical field will naturally occur to those interested in such processes. As a matter of interest a short list is given below of applications outside the field of electrochemistry but which bear upon this problem.

In the recovery of the sand used in the washing of coal it is necessary to keep the percentage of solid matter in the waste water between specified limits in order to obtain maximum recovery. The opacity of a thin stream of the effluent liquid is a definite criterion of the per cent solid matter contained.

In municipal water plants using chlorination it is necessary to regulate the amount of excess chlorine. The addition of an indicator to a sample of such water gives a color corresponding to the amount of excess chlorine present.

In paper mills the acidity of the paper stock solution and the concentration of the black liquor must be closely controlled. The acidity of the paper stock solution can readily be determined by the addition of an indicator to a sample and the opacity of the black liquor is a function of its concentration.

Two concentration regulator schemes have been worked out for applications in this class of service. The first or "balanced bridge" arrangement utilizes two light sensitive photo tubes simultaneously to inspect the light transmitted through a sample of the unknown liquor and the light transmitted through a standard colormetric sample representing the desired quantity of the variable chemical. The second or "null" method uses a single photo tube inspecting simultaneously the light transmitted by the unknown sample and the known sample. The "balanced bridge" arrangement utilizes established light sensitive circuits assembled in such a way as to perform the new function. It has the slight disadvantage of requiring recalibration from time to time because of the possibility of discrepancies in characteristics developing with age of the tubes. No such recalibration is necessary with the "null" method because, as the term implies, the regulation effects a zero response from the equipment when the percentage of the varying chemical is correct. The advantage of the "balanced bridge" arrangement is that it can also be used as an indicator whereas the "null" method does not permit its use as an indicator without the recalibration which it is designed to avoid as a regulator. Otherwise the two schemes are very similar in economy, speed and accuracy.

Fig. 1 shows a "balanced bridge" arrangement of photo tubes designed to regulate the hydrogen ion con-

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†*Recent Developments in Electronic Devices for Industrial Control* by F. H. Gulliksen, A.I.E.E. paper **33-24**, gives a list of other fields of applications of light sensitive control.

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centration of a flotation liquor, by controlling the speed of a conveyer which feeds lime to the process and maintaining this speed constant between corrective impulses received from the photo tubes. The schematic diagram is complete up to and including the motor drive for the lime conveyer. The mechanical equipment such as sampling, filtering, adding of indicator and placing before the photo tube are omitted because these features will change with individual applications. It should be noted here that only minor changes of the equipment shown in the diagram are required to make it applicable to the control of solenoid- or motor-operated valves or motor-operated rheostats and similar equipment encountered in regulating the flow of solids, liquids and gases.

The principle of operation is briefly as follows: Two photo cells are connected in a wheatstone bridge circuit which is supplied with direct current by a *B* eliminator. Potentiometer 1 constitutes one side of the bridge, and the two photo tubes the other side. The two photo tubes are illuminated from the same light source, not shown in the diagram. In front of one photo tube is placed a standard color sample in a glass tube, while the fluid to be controlled flows through a similar glass tube in front of the other photo tube. It is apparent that any variations in light intensity due to varying lamp voltage will not have any effect on the balanced bridge circuit. If the alkalinity of the fluid changes the bridge becomes unbalanced so that the voltage on the grid of tube No. 2 will differ from the grid voltage on tube No. 3. The result of this unbalance is that the grid of one of the grid glow tubes becomes more negative and the grid of the other tube becomes positive. Positive grid bias on the grid glow tube causes a breakdown of the tube so that for example relay III will become energized and close its contacts. It should be noted that tubes No. 2 and No. 3 are connected in a wheatstone bridge circuit which is normally balanced. For this reason, variations in supply voltage will not affect the calibration of this part of the equipment.

When relay III operates, relay V is closed and seals itself in, and voltage is applied to tube 4 which, in combination with relay II, acts as a time delay device. Depending upon the adjustment of potentiometer 6 a time delay up to one minute can be provided between the instant of closure of relay V and the instant of closure of relay II. Relay V in closing also operates the motor-operating relay VII, which causes the motor-operated rheostat to move and readjust the speed of the driving motor. Relay VII will remain closed until relay II is energized, since "break" contacts of relay II are connected in series with the coil or relay VII. During this period the motor speed is being readjusted.

When a correction has been made it is essential to prevent a second correction from being made until the effect of the first correction has been recorded by the photo tubes. For this reason a second time-delay relay is provided which may be adjusted for a time delay up to five minutes and which is so connected in the circuit that during this time interval no rheostat operation can take place. This second time-delay relay consists of relay I, tube No. 5 and associated equipment. It will be noted that the timing of this combination starts with the closure of relay II. When relay I operates, relay V

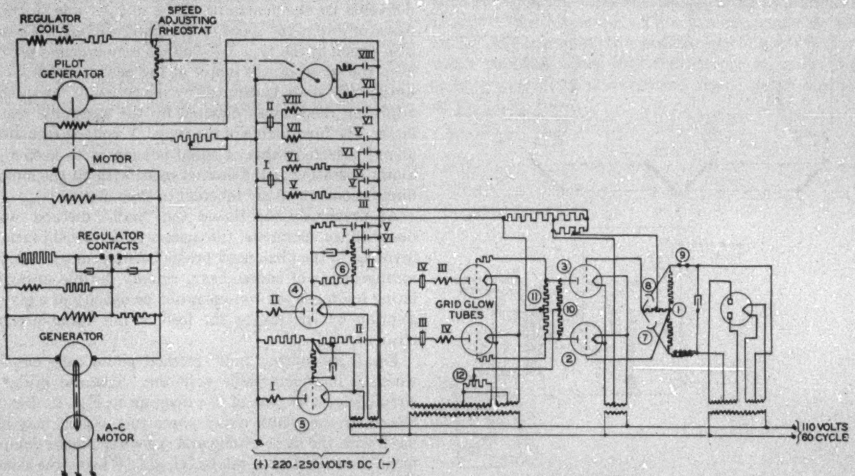

Fig. 1—Concentration Analysis Regulator Balanced Bridge Circuit

will be deenergized, and the equipment will be ready for the next adjustment.

Supposing the standard sample is arranged in front of photo tube 8, a recalibration of the equipment may be made either by changing the standard sample or by adjusting potentiometer 1. The instrument should be calibrated by opening switch 9, and connecting a high-resistance voltmeter across resister 10, by means of telephone jacks supplied for this purpose. Potentiometer 11 is then adjusted until the voltmeter reads zero.

The sensitivity of the regulator may be adjusted by means of potentiometer 12 which changes the constant negative grid bias which is applied to the grid glow tubes.

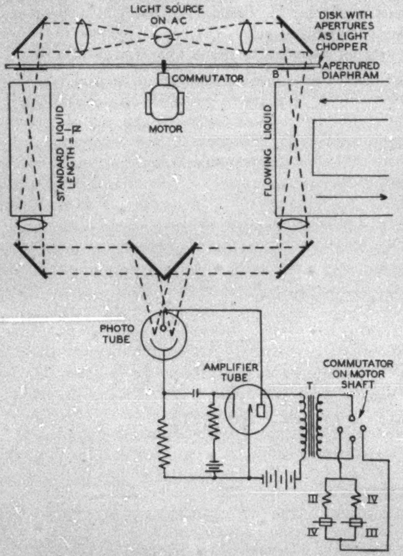

Fig. 2—Concentration Analysis Regulator Null Method

Proper operation of the electronic regulator described above is predicated upon the requirement that the motor operating the feed runs at the definite speed dictated by the regulator. These speeds must be maintained at the level indicated by the regulating equipment and not be permitted to vary from the dictated amount. Small motors do not possess flat speed torque characteristics particularly at varying armature voltages. Therefore, speed regulating equipment is added to the motor driving the feed.

The apparatus shown at the top of Fig. 1 outlines this speed-regulating equipment. The motor-generator set provides the armature voltage for the feed motor. This motor itself is to have coupled to it, a small pilot generator which will be excited from the 250-volt d-c supply. The voltage of the generator supplying the armature of the feed motor is regulated by a type UV voltage regulator. The coils of the regulator are connected across the armature of the pilot generator in series with a motor-operated speed-adjusting rheostat.

The functioning of this speed-regulating equipment in conjunction with the electronic equipment is as follows. Assume the regulating equipment to be in operation and the fluid being regulated to be of the proper color. Now assume that the color of the regulated liquid changes. As outlined in the preceding paragraph, this change will result in the operation of the motor controlled by relay VII or VIII. This motor is located on the speed-adjusting rheostat which modifies the current through the regulator coils connected across the pilot generator armature. The result of the movement of this rheostat is to change the calibration of the type UV voltage regulator which in turn modifies the voltage delivered by the generator of the m-g set and in turn raises or lowers the speed of the motor driving the feed. The action of the type UV voltage regulator is then to keep the speed of this motor at the newly chosen level until a new speed is dictated by the action of the speed-adjusting rheostat as directed by the electronic regulator. The functioning of the type UV voltage regulator at any selected value of speed is such as to keep the motor operating at the desired speed without the minor fluctuations which are inherent in such motors.

As previously mentioned the "null" method was designed to eliminate the necessity for recalibration involved in the "balanced bridge" arrangement. Both arrangements of course being equally flexible in regulating hydrogen ion concentration or opacity of a given solution by controlling the feed of the variable constituent.

Fig. 2 shows the "null" method photo tube circuit which is interchangeable with the "balanced bridge" circuit shown as part of the diagram in Fig. 1. For a colormetric regulator either photo tube circuit may be used, with the same timing and speed regulating equipment shown in Fig. 1, relays III and IV being the same in both figures.

Briefly the "null method regulating equipment" operates on the following principle: The lightbeams from a single light source are directed by a system of mirrors and lenses through two different paths onto a single photo tube in such a manner that one beam passes through a standard color sample and the other beam passes through the unknown liquid. An apertured diaphram is rotated in the path of the two beams so as to vary the cross section of the beams permitted to pass through the two liquids. The sum of the apertured areas *A* and *B* are always equal to unity, the aperture *A* varying from zero to 100 per cent while the aperture *B* varies from 100 per cent to zero.

Thus if the light transmitting qualities of the two liquids are identical the illumination of the photo tube will be unchanged as the diaphram is rotated, and therefore the output of the amplifier tube or its plate current will be constant direct current. With constant direct current impressed on the primary of transformer *T* there will be no output from the secondary, and relays III and IV will not be energized.

If the light transmitting quality of one of the liquids deviates a small amount from that of the other the illumination of the photo tube will vary as the diaphram is rotated and the plate current of the amplifier tube will therefore become a pulsating direct current. With pulsating direct current impressed on the primary of the transformer *T* the secondary will deliver only the alternating component, which in phase position and in magnitude will be proportional to the deviation in light transmitting qualities of the unknown fluid from that of the standard fluid. Since this alternating component is rectified by a mechanically driven commutator on the shaft of the motor which drives the diaphram, the direct current obtained will be proportional in sign and magnitude to this same deviation in light transmitting quality. With relay III set to pick up at a minimum value of positive current, and relay IV set to pick up at a minimum value of negative current, the speed adjusting rheostat and timing cycle explained under Fig. 1 will be set in operation just as these operations were started when relays III and IV of Fig 1 were energized by the breakdown of the grid glow tubes.

Since this circuit is a zero or "null method" and this feature is obtained by filtering out the direct component of the plate current of the amplifier tube, the regulator is insensitive to steady variations in applied voltage as affecting the circuit or the light source, and it is not affected by steady variations in temperature or changes in sensitivity of the tube itself within its working range.

## CONCLUSION

The concentration regulator schemes presented provide the accuracy, reliability and economy required of such devices. In addition they provide an adjustable amount of correction for each sample observed, together with an adjustable inoperative time, while awaiting the effects of one correction. Thus the equipment as designed may be applied to a wide variety of uses with the major problem being only the manner in which the unknown sample is prepared and placed before the eye of the photo tube.

# Skin Effect in Rectangular Conductors

## A Method of Measurement and Experimental Data

BY H. C. FORBES* and L. J. GORMAN*
Member, A.I.E.E. Member, A.I.E.E.

THE investigation covered by this paper was initiated, primarily, with a view to determining the skin effect at commercial frequencies in conductors of rectangular cross-section for cases where the return circuit is comparatively remote so that proximity effect need not be considered. These conditions are approximated in the case of bus bars of rectangular conductors in generating stations and substations where an isolated phase layout is employed. It was in connection with the design of such buses that the need for more complete information developed. In the process of obtaining the information desired, it was also possible to obtain basic data from which the skin effect in any non-magnetic rectangular conductor of ordinary dimensions can be readily determined for a wide range of frequencies. Accordingly, it was believed that the results obtained would be of general interest.

Considerable work, both of an experimental and theoretical nature, has previously been done on this subject, and particular mention is made of papers by H. B. Dwight,[1] and by A. E. Kennelly, F. A. Laws, and P. H. Pierce,[2] and of the accompanying discussion, particularly that contributed by Joseph Slepian, which have been published by the American Institute of Electrical Engineers.

It has been shown in these papers that the ratio of a-c to d-c resistance of a conductor may be determined as a function of the parameter, $P = \sqrt{\frac{8\pi f A}{\rho}}$, in which the symbols are defined as follows:

| | |
|---|---|
| $f$ | frequency in cycles per second |
| $A$ | area of cross-section in square centimeters |
| $\rho$ | specific resistivity in abohms per $\text{cm}^3$<br>(specific resistance in ohms is $\rho \times 10^{-9}$) |

This relationship suggested the possibility mentioned by Dwight of making tests at high frequencies on conductors of relatively small cross-section and applying the results to obtain the skin effect in large conductors at lower frequencies. This scheme of testing obviously offers great advantages because of the difficulties in making a-c measurements at the very low voltages which would be involved if large size conductors were tested at commercial frequencies. Accordingly, in this investigation the above principle was applied to tests on small rectangular conductors of various width-to-thickness ratios, tested at frequencies ranging from 22 to 287 kilocycles.

Two methods of measuring a-c resistance at high frequency were investigated; namely, the "substitution method" and the "resistance variation method," both of which are described in detail in the publications of the Bureau of Standards.[3] Essentially, each employs a test circuit, which includes the test specimen, coupled to a suitable source of high-frequency current, such as a vacuum-tube oscillator.

For the particular low-resistance circuits involved in this investigation, the "substitution method" seemed to give the most satisfactory results, and was best adapted to the use of the laboratory equipment on hand. In this method, it is not necessary to measure precisely the current or voltage, but only to provide a means of indication by which the emf may be controlled, and the test current adjusted and held at a convenient value for a particular test. Furthermore, it was found that the introduction into the test circuit of any of the high-frequency ammeters available added materially to the total resistance of the circuit, and thereby greatly decreased the sensitivity of the measurement. This proved to be a limitation in the use of the "resistance variation method." The use of an ammeter in the "substitution method" was avoided by the current-indicating device described below.

FIG. 1—OSCILLATOR AND EQUIPMENT FOR TEST CIRCUIT

Although the method of measurement is relatively simple, there are various precautions incidental to the use of high-frequency currents that must be observed in the practical application to avoid erroneous results. These precautions apply particularly to the shielding

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*The New York Edison Company, New York, N. Y.

[1] H. B. Dwight, TRANS. A.I.E.E., 1918, p. 1379.

[2] A. E. Kennelly, F. A. Laws, and P. H. Pierce, TRANS. A.I.E.E., 1915, p. 1953.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

[3] Bureau of Standards Circular No. 74.

and grounding of the various parts of the test equipment, and to the measurement and control of the high-frequency currents.

The oscillator and equipment used in the tests are shown in Fig. 1. A schematic circuit diagram is shown in Fig. 2. Essentially, the equipment consisted of a master oscillator coupled to a two-stage power amplifier, the second stage of which contained two 50-watt pliotron tubes. The primary of an air core transformer was connected to the output circuit of the amplifier. Special care was taken in the construction of the oscillator and in the selection of tubes and other equipment to insure a wave shape as free of harmonics as possible. With the oscillator operating at frequencies between 20 and 180 kilocycles, a test was made for harmonic frequencies up to 3,000 kilocycles. No harmonics of importance were found within this range of frequency. Precautions were taken to avoid possible errors due to "proximity effects," "end effects," and the influence of metallic structures located near the test circuit. These various influences and their effect on the measurements were checked in a series of preliminary tests.

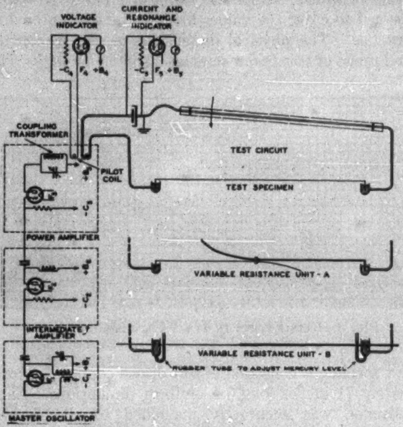

FIG. 2—SCHEMATIC DIAGRAM OF OSCILLATOR AND TEST CIRCUIT FOR SKIN EFFECT MEASUREMENTS

The test circuit shown in Fig. 2 comprises a loop containing the test specimen, a low-loss tuning condenser, and a length of heavy Litzendraht cable, required to complete the circuit. The oscillator coupling was made through a single turn of cable loosely coupled to the transformer primary. The condensers in the test circuit were selected with reference to the size of the loop, so that the circuit was approximately in resonance at the desired test frequencies. Adjustment for resonance was made by moving in or out the arm on one side of the loop, as indicated by the arrow in Fig. 2, thereby varying the size and inductance of the loop. This arrangement permitted a very fine adjustment of resonance, avoided the use of tuning coils, gave a test circuit of minimum resistance, and permitted the desired sensitivity in the measurements.

The emf induced in the test circuit was determined by means of the voltage indicator shown in Fig. 2. This consisted of a pilot coil closely coupled to the secondary turn and connected to the grid circuit of a vacuum tube, as shown. The indications on the milliammeter in the plate circuit of the vacuum tube were proportional to the emf induced in the pilot coil, and, since the same flux was interlinked with the secondary turn, the readings were proportional to the emf induced in this turn. By means of the indicator, it was thus possible to maintain a constant resultant flux interlinked with the secondary turn, and, therefore, a constant emf in the test circuit, by adjusting the plate voltage on the amplifier.

It was apparent that the resistance of the test circuit would have an important influence on the sensitivity of the measurement. The resistance of the circuit, not including the test specimen, was, therefore, kept as low as possible so that the resistance of the test specimen would constitute a large portion of the total circuit resistance. It was found that inserting an ammeter into the test circuit added appreciably to its resistance. Since in the method of measurement it is not essential to know the test current in amperes, the use of an ammeter was avoided by using a vacuum-tube indicator, the grid circuit of which was connected across the fixed condenser in the test circuit, as shown in Fig. 2. Since at any given frequency the drop across the condenser would be proportional to the current, this gave a means of indicating the point of resonance and served as a basis for making the adjustment of the variable resistance required to give a current equal to that obtained when the test specimen was in circuit. This arrangement proved quite satisfactory. An approximate calibration of the indicator was made by connecting a low-resistance, high-frequency ammeter in the circuit, and plotting readings on the indicator against ammeter readings at each of the various test frequencies. During the actual measurements, however, the ammeter was removed.

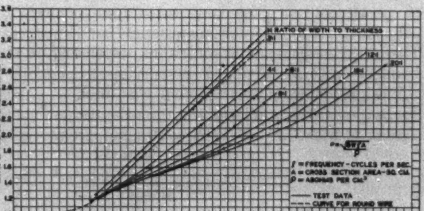

FIG. 3—SKIN EFFECT IN STRAP COPPER CONDUCTORS

The selection of a suitable resistance unit for use as a reference standard was an important factor in these measurements. The principal requirements were that the resistance be continuously variable, easily adjusted, and its construction such that when substituted for the test specimen it would not materially change the constants or configuration of the test circuit. These requirements were met by the round wire resistance units shown in Fig. 2 (*A* and *B*). Each type of unit was constructed of two sizes of copper wire, one somewhat larger, and the other somewhat smaller in cross-section than the test specimens. The type shown at *A*, Fig. 2, was provided with a slider by which the relative lengths of large and small wire could be easily adjusted. The second type consisted of two sizes of copper wire joined together, and placed in mercury cups so that sliding the unit either way varied the relative length of the large and small wire. The a-c resistance of straight round wire can be readily calculated from published formula.[3] The a-c resistances of the adjustable resistor units were therefore obtained by calculating the resistance of separate lengths of large and small wires measured between the contacts. This result was checked by reference to straight round wire specimens of uniform cross-sectional area, the a-c resistances of which were calculated. The accuracy of the method was found to be approximately one per cent.

Mercury cups were provided by which the test bars and the adjustable resistance unit could be easily interchanged. The resistances of the other connections were made as low as possible by the use of tinfoil between the contacts. The contact resistance, including that of the mercury cups, was approximately one per cent of the total resistance of the circuit. The resistance of the Litzendraht cable constituted approximately 58 per cent of the total circuit, and the test bar 41 per cent. These percentages varied somewhat, depending on the frequency and the particular test specimens in circuit.

The procedure of measurement was, first, to adjust the output of the oscillator and tune the test circuit to resonance with the test specimen in the circuit. The adjustable resistance was then substituted for the test specimen, and, with the output of the oscillator held constant, the resistance was varied until the same conditions of resonance were obtained in the test circuit. Since all other constants of the circuit were the same, the resistance of the variable standard unit was then equal to that of the test specimen, and its value was calculated from the relative lengths of large and small wires, as explained above.

The tests were made on specimens representing a range of width-to-thickness ratios of 1:1 to 20:1, which seemed to cover the values likely to be encountered in practise. The physical dimensions of the specimens, and range of test frequencies are listed in Table I. The test specimens consisted of soft drawn copper, approximately 71 inches long, of uniform dimensions. Each specimen was accurately machined to the desired width-to-thickness ratio, and precautions taken to insure sharp square edges. The d-c resistance was obtained by the usual bridge method, special care being given to securing specimens of uniform resistivity. Test specimens having different cross-sectional areas, but the same ratio of width to thickness, were selected so that experimental checks of the theory could be obtained by making measurements at different frequencies to satisfy the conditions of the parameter.

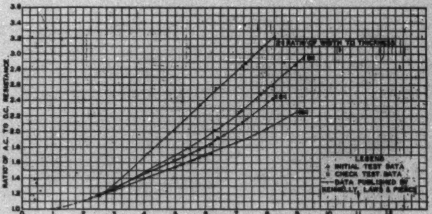

FIG. 4—SKIN EFFECT IN STRAP COPPER CONDUCTORS

The data obtained from the tests are given in graphical form in Fig. 3, in which the ratios of a-c to d-c

TABLE I—DIMENSIONS OF TEST BARS AND RANGE OF FREQUENCIES USED IN MEASUREMENT OF A-C TO D-C RESISTANCE RATIOS

| Test bar number | Average dimension inches a | b | Average area square inches | Actual ratio a/b | Nominal ratio a/b | Length inches | Test frequency range Kilocycles |
|---|---|---|---|---|---|---|---|
| 1A | 0.0606 | 0.0602 | 0.00365 | 1.007 | 1 | 71 | From 22 to 179 |
| 2A | 0.0805 | 0.0404 | 0.00325 | 1.99 | 2 | 71 | 22 to 179 |
| 3A | 0.1205 | 0.0300 | 0.00362 | 4.02 | 4 | 71 | 22 to 179 |
| 4A | 0.1491 | 0.0256 | 0.00382 | 5.83 | 6 | 71 | 22 to 232 |
| 5A | 0.1600 | 0.0202 | 0.00323 | 7.93 | 8 | 71 | 22 to 232 |
| 1B | 0.1399 | 0.0718 | 0.01004 | 1.95 | 2 | 71 | 26 to 75 |
| 2B | 0.2706 | 0.0454 | 0.01228 | 5.96 | 6 | 71 | 26 to 75 |
| 3B | 0.2812 | 0.0357 | 0.01002 | 7.88 | 8 | 71 | 26 to 75 |
| 1C | 0.242 | 0.021 | 0.00508 | 11.72 | 12 | 71 | 45 to 287 |
| 2C | 0.322 | 0.021 | 0.00676 | 15.31 | 16 | 71 | 45 to 179 |
| 3C | 0.403 | 0.021 | 0.00846 | 18.18 | 20 | 71 | 45 to 179 |

resistance are plotted as a function of the parameter. The curves in Fig. 4 show a comparison between the data obtained in these tests and those published by Kennelly, Laws, and Pierce for width-to-thickness ratios of 8 and 16. The curves also show the agreement obtained between tests on specimens of the same width-to-thickness ratios, but of different cross-sectional areas. A very close agreement was obtained with the published data and between specimens of different sizes. It is felt that the consistent results thus obtained speak well for the reliability of the data.

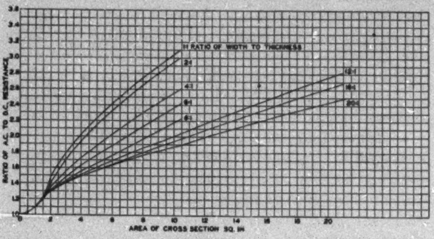

FIG. 5—SKIN EFFECT IN STRAP COPPER CONDUCTORS AT 60 CYCLES

From an inspection of the data given in the paper by H. B. Dwight (see reference 1), it might have been anticipated that, except for the initial curvature near the origin, these curves would be straight lines. Apparently, however, this is by no means the case, although it is approximately true within the limits of the tests in the particular instance of the conductors having width-to-thickness ratios of 1:1 and 2:1. For other width-to-thickness ratios, the curves tend to bend upward for values of parameter above 5.5. The close agreement between the curve for a round wire and the curve for the 2:1 specimen is interesting to note, and also the fact that the skin effect in a square conductor is consistently greater than that of a round wire.

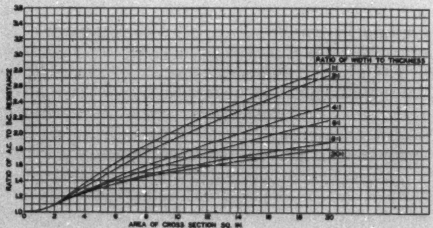

FIG. 6—SKIN EFFECT IN STRAP COPPER CONDUCTORS AT 25 CYCLES

In order to reduce the data to convenient form for determining skin effect at commercial frequencies, Figs. 5 and 6 were prepared. From these curves, the skin effect in rectangular conductors at 60 cycles or 25 cycles can be readily determined. Similar curves for any frequency can be easily calculated from the basic data given in Fig. 3.

## Discussion

**J. E. Clem:** The authors state that the ratio of alternating-current resistance to the direct-current resistance of a conductor may be expressed as a function of the parameter $P = \sqrt{\frac{8\pi f A}{\rho}}$. This statement, while perfectly true, without further qualification, might lead to a misunderstanding, since apparently it indicates that the eddy-current loss might vary as the square root of the frequency.

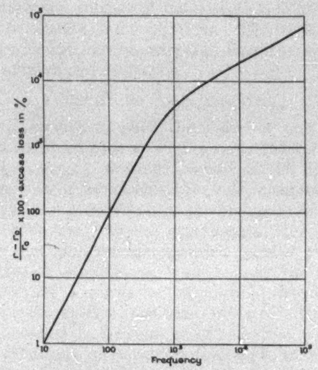

FIG. 1

If the extra loss be segregated it can be shown that the extra loss varies with the square of the frequency in the neighborhood of 60 cycles and that for very high frequencies this extra loss varies as the square root of the frequency. This is illustrated in Fig. 1. Since this is the case it is essential that extreme caution be used in applying the results of tests made at high frequencies or extreme conductor proportions to determine the excess loss at commercial frequencies.

There is a tendency among some writers to consider skin effect, proximity effect, eddy-current loss, and unequal distribution of current as separate phenomena. There is no justification for this, since they are all produced by the magnetic flux passing through the conductor. Several years ago, I developed a method of calculating the eddy-current loss in transformer conductors. Fig. 1 was calculated using this method. These same equations have been used to calculate the extra loss due to unequal division of current in parallel conductors and when properly applied give the same losses as formulas developed to calculate the supposed entities, skin effect, and proximity effect.

**H. C. Forbes and L. J. Gorman:** The authors wish to point out that while their paper states that the ratio of alternating current to direct current resistance may be determined as a function of the parameter $P$, which is defined in the paper, it makes no statement whatever in regard to the determination of eddy current loss which under the conditions of the tests is believed to have been wholly negligible. In the same way as is pointed out in the paper it was the intent to keep the return circuit for the current remote so that the proximity effect also would be negligible. It is believed accordingly that the increase in resistance as compared to the d-c resistance as obtained by the tests is all due substantially to the non-uniformity of distribution of current in the conductor resulting from the phenomenon commonly termed skin effect.

It seems to the authors that Mr. Clem's suggestion that there is no justification for separate consideration of skin effect, proximity effect, and eddy current leads to hopeless confusion in the analysis of such losses.

# A Standard of Low Power Factor

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Member, A.I.E.E. Associate, A.I.E.E.

## INTRODUCTION

IN the study of the electrical characteristics of insulation, an accurate knowledge of the power factor and loss is of importance. The measurement of these factors is affected by many variables and unsuspected errors are often present in the results. A survey of the literature on the subject of dielectric loss measurement reveals clearly the lack of a reliable reference standard.

The need for a standard load which should simulate the power factors found in cable samples as well as in insulating oils has long been recognized. From time to time a number of schemes and devices has been suggested for verifying the accuracy of the loss measuring equipment. Some of these depend upon the check obtained by the measurement of the increase in loss produced by connecting a resistance in series[1,2,3] with the sample under test. The introduction into the circuit of a series resistance, aside from the fact that it may have an appreciable phase angle, disturbs the potential distribution and leaves much to be desired from the standpoint of accuracy. Another scheme is to measure two or more specimens singly and then in parallel. The accuracy of this check is open to question because of the many variables such as temperature and voltage that affect the dielectric loss of a given specimen.

Attempts have been made at various times to construct suitable standards of glass or similar materials with the hope of obtaining a satisfactory load. Of these, the ones developed by the Electrical Testing Laboratories of New York[3,4] are by far the best. Their power factor, however, cannot be computed but has to be measured in the very circuit which itself is subject to error. It is clearly analogous to the efforts of a man to lift himself by his own bootstraps.

All of the above methods for checking dielectric loss measuring equipment are qualitative in their nature and none of them can be considered as a basic standard. In addition, their correctness rests upon the very equipment whose accuracy they are supposed to verify.

A new standard of low power factor has recently been developed in the Electrical Laboratories of The Johns Hopkins University which it is hoped will meet the needs of workers in the field of insulation. It consists essentially of a loss-free shielded and guarded compressed air capacitor connected in series with an ideally shielded resistor. It is the purpose of this paper to present a description of the new standard as well as some data concerning its performance in checking Schering bridges. The standard may, however, be used for verifying the accuracy of other types of low loss measuring apparatus.

Since a dielectric specimen can be most easily and satisfactorily represented by the combination of a capacitance and a series resistance, these were chosen to form the basic elements of the standard. In order that this circuit possess characteristics desirable in such a standard load, the capacitance should be loss-free and properly shielded, the resistance should be essentially pure and its introduction into the circuit should not disturb the equality of the potentials of the guard and main circuits of the capacitor. The power factor of such a circuit can be computed from the values of its capacitance and resistance.

## COMPRESSED AIR CAPACITOR

It was decided to build the capacitor unit of the low-loss standard with a capacitance of 500 $\mu\mu$f; which could be operated without corona at 25 kilovolts effective. In order to reduce its bulk, compressed air at a maximum pressure of ten atmospheres was chosen as the dielectric. Earlier experiments have demonstrated that shielded and guarded parallel plate air capacitors at atmospheric pressure and low relative humidity are loss-free at commercial frequencies.[5] Careful tests, which will be described later, proved that the compressed air dielectric is also loss-free.

The cylindrical air capacitor developed for this work is shown in Fig. 1. The area of the guard electrodes equals very nearly that of the main electrode thus giving approximately a one to one ratio between the guard and main capacitances. The flared shields at the extreme ends are connected to ground. These eliminate the possibility of any leakage current from the high-voltage electrode reaching either the guard or measuring electrodes. They also serve to increase the electric strength of the capacitor. Fig. 1 shows that the guard electrode is extended in the form of a shield so as to cover completely the back of the main electrode, and that the lead from the main electrode is shielded by the continuation of the guard in the form of a tube.

The air capacitor as constructed consists of three coaxial brass tubes, the middle one acting as the high voltage electrode. This is 23 in. (58.5 cm) in length, 8 in. (20.32 cm) outside diameter, and 1/8 in. (0.32 cm) thick. There are two low-voltage tubes, one inside and the other outside of the high-voltage electrode. Each low-voltage tube consists of five sections. The central section, 9 in. (22.86 cm) in length, forms the measuring electrode. This is protected by two guard ring sections,

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1. For references see Bibliography.

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one above and the other below, and two bell-shaped grounded shields, one at each end of the assembly. Each guard section is 4½ in. (11.43 cm) in length. Each section of both low voltage tubes is separated from the adjoining section by a gap of 1/16 in. (1.6 mm) maintained by the use of bakelite rings. Each bell-shaped shield has an axial length of 2 in. (5.08 cm), making the overall length of the complete low voltage tube 22¼ in. (56.5 cm). The assembly of the inner low-voltage electrode is shown in Fig. 2.

The spacing between the high- and low-voltage electrodes is fixed at 0.2 in. (5.08 mm) by means of grooves cut in bakelite disks between which the tubes are clamped. In Fig. 2 the lower disk may be seen in place. The high- and low-voltage electrodes are clamped together between the upper and lower bakelite spacing disks by means of four one-half-inch brass rods. The assembly is mounted on a twelve-inch blind pipe flange as is shown in Fig. 1. This figure also shows the complete shielding of the main electrode and its lead.

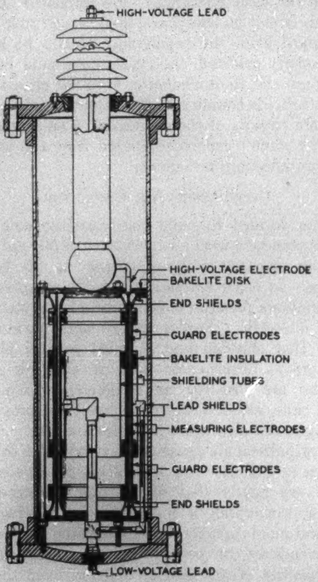

FIG. 1—SECTIONAL VIEW OF THE COMPRESSED AIR CAPACITOR

The capacitor is enclosed in a standard twelve-inch wrought iron pipe 4 ft (1.2 m) in length. This has ample strength to withstand the pressure used. The high-voltage bushing is a 50,000-volt circuit-breaker bushing furnished by the Locke Insulator Company. Care was taken to eliminate all sources of corona inside of the capacitor, all edges were rounded or protected.

The use of compressed air in capacitors is not new. Fessenden[6] and Max Wien[7] were among the pioneers in its use. With the introduction of guard ring capacitors further developments and improvements were made by Schering[8] and others. Palm[9] found that the dielectric strength of air increased almost directly as the pressure, for pressures up to ten atmospheres. There is a slight change in the dielectric constant $\epsilon$ with pressure. Its variation is given by the expression[10]

$$\epsilon = \frac{1 + 2\,c_1 d_1}{1 - c_1 d_1}$$

where $c_1$ = constant = $195 \times 10^{-6}$

and $$d_1 = \frac{P}{1 + 0.003665\,T}$$

where $P$ = pressure in atmospheres for the range 0 to 175 atmospheres

and $T$ = temperature for the range 0 to 70 deg C.

The variation in dielectric constant for a pressure change from atmospheric to ten atmospheres amounts to less than one-half of one per cent. Consequently, the effects on the capacitance of the standard of any pressure changes due to air leakage are negligible.

## TESTS OF THE CAPACITOR

After assembly the capacitance of the air capacitor was measured by two entirely different methods. The capacitance of the main plate was found to be 517.5 μμf and that of the guard 530 μμf. This is sufficiently close to a one-to-one ratio for our purpose and the ideally shielded resistors were adjusted in accordance with these values as will be explained later.

At an air pressure of ten atmospheres the capacitor withstood 30 kilovolts continuously without any indication of corona. When the voltage was raised to 35 kilovolts a flashover occurred across the surface of the bakelite spacing disk between one end-shield and the high-voltage tube. The damaged bakelite spacing disk was repaired and a second test, made at 30 kilovolts, also gave no evidence of corona or other trouble. It is, therefore, clear that the capacitor can safely withstand its working potential of 25 kilovolts.

Experiments conducted both here[5] and abroad[11] have demonstrated that at atmospheric pressure and low relative humidity, an adequately shielded air capacitor is loss-free as far as measurements on commercial insulation are concerned. The compressed air capacitor was, therefore, compared with shielded flat-plate capacitors of this type. The tests were made at 60 cycles in two Schering bridges, one having a maximum voltage range of 1,000 volts and the other of 10,000 volts. Each of these bridges is completely shielded and guarded and has a power factor sensitivity of ± $5 \times 10^{-6}$. The compressed air capacitor was inserted in place of the specimen in each bridge in turn and its power factor determined at temperatures ranging from 10 deg to 27 deg C, and pressures from atmospheric to 175 lb gage, care being taken to remove the moisture from the compressed air. In every case the power factor of the compressed air capacitor was found to be zero to within the accuracy of the bridges. We, therefore, concluded that an adequately shielded and guarded compressed gas capacitor is loss-free and that it acts as a pure capacitance. Its capacitance is independent of voltage and temperature variations and its characteristics are those of a standard.

Fig. 2—Inner Low-Voltage Tube of the Capacitor

## Series Resistors

The power factor of a load consisting of a capacitance and a series resistance may be accurately computed provided their values are known and that they are free from defects. Tests proved that the compressed air capacitor could be considered as a pure capacitance. The problem of constructing the second element of the combination, namely, a pure resistance for alternating current work, was more difficult.

A resistor in addition to its ohmic resistance possesses three parasitic properties, self-inductance, self-capacitance and earth-capacitance. The first and second may be made small by the use of the proper winding. The third is the most troublesome and its elimination is a difficult problem.

The capacitance to earth of a resistor varies with the position of the coil with respect to surrounding objects. The simplest way of fixing its value is to enclose the unit in a metal container maintained at a definite potential with respect to the voltage drop across the coil.

In a shielded and guarded capacitor of the type constructed it is of prime importance that exact equality of potential be maintained between the guard and main electrodes and their leads. Otherwise, there will be a transfer of energy through the capacitance existing between these two circuits which will cause errors in the results, as pointed out by Kouwenhoven and Baños.[12]

Fig. 3A shows a shielded resistor in which the shield is maintained at a potential equal to that of the mid point of the working resistance $R_W$ by means of a tap from the guard resistance $R_G$. This connection to some extent balances earth capacitance effects of the resistance $R_W$, the equation being given in the appendix. At the same time, by use of the proper value of guard resistance, $R_G$, the equality of potentials between the guard and main electrodes is maintained.

A better arrangement is obtained by subdividing the resistance into sections, shielding each section separately and maintaining each shield at its proper potential. Shielded resistances of this type have been described by Orlich,[13] Kouwenhoven,[14] Hiecke,[15] Silsbee[16] and others.

If we carry subdivision of the resistor to the limit where each element of the working resistance $R_W$ is shielded by a corresponding element $R_G$ in the guard circuit, we have the best arrangement and what may be called an "ideally" shielded resistor. Fig. 3B illustrates schematically such a resistor. The guard resistance is coaxial with and completely surrounds the working resistance. Both the guard and working resistances are uniformly distributed and their values chosen so as to maintain equal potential drops along their lengths. Under these conditions there is no voltage across the capacitance between the two resistances because the potential is the same at all corresponding points along the two circuits. Therefore, with this method of shielding, earth capacitance effects are reduced to a minimum. This type of resistance was chosen as the second element of the standard of low power factor and three units, one of 1,000 ohms, one of 5,000 ohms, and one of 10,000 ohms nominal values, were constructed.

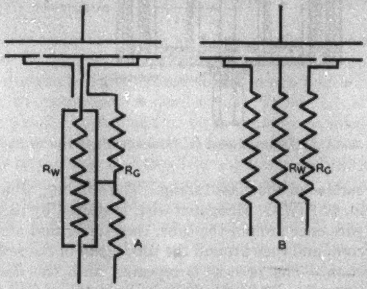

Fig. 3

A—Simple Type of Shielding

B—Ideal Type of Shielding

A theoretical discussion of the simple shielded resistor and of the ideally shielded resistor, Fig. 3 (A and B), is given in the appendix.

### IDEALLY SHIELDED RESISTOR

The working resistance, $R_W$, is wound on a one-inch outside diameter pyrex glass tube in accordance with a method developed by Dr. Frank Wenner of the Bureau of Standards. A heavy cord is placed axially along the surface of the glass tubing. The winding, which is of No. 40 A.W.G. Manganin wire, is started by passing the wire once around the tube, then under and around the cord, and then around the tube again in the reverse direction. The process is repeated until the desired resistance is obtained. Every alternate turn of this type of winding is reversed, thus reducing its self-inductance and self-capacitance to a minimum.

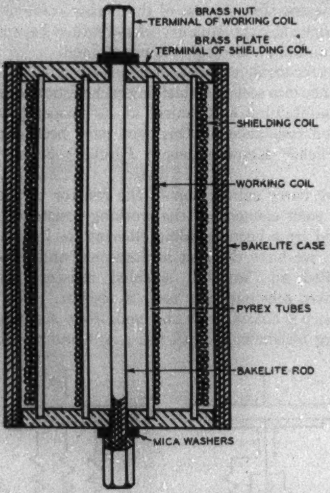

FIG. 4—A 5,000-OHM IDEALLY SHIELDED RESISTOR IN SECTION

The guard resistance, $R_G$, is wound on a two-inch diameter pyrex tube. This winding has the same axial length as that of the working circuit. It consists of a double layer winding with the layers wound in opposite directions and connected in parallel after annealing and adjusting.

A sectional view of the 5,000-ohm ideally shielded resistor is given in Fig. 4. The tubes carrying the working and guard windings are mounted coaxially between brass plates. The resistors are enclosed by bakelite panels fastened to the brass plates. Convenient terminals are provided for connecting any one of them in series with the capacitor. Fig. 5 is from a photograph of the three ideally shielded resistors constructed for the low-loss standard. The values of the resistances of the circuits of the three ideally shielded resistors are given in Table II.

### TESTS OF THE IDEALLY SHIELDED RESISTORS

The phase angles of the ideally shielded resistors were measured in a special alternating-current bridge developed for the purpose. This bridge and the method of measurement is described elsewhere.[17] The resistors were tested at both 60 and 500 cycles and their effective inductance was measured with a fixed value of current, $I_W$, flowing through the working resistance while the current $I_G$ through the guard circuit was varied. The effective inductance[18] of a resistance is given approximately by the expression $L-CR^2$, where $L$ is the inductance, $C$ the capacitance and $R$ the resistance of the unit.

The results of the tests are given by the curves of Fig. 6. From the curves it is evident that the effective inductance of the resistors is negative when the guard circuit is carrying less current than the working circuit. However, when the guard current becomes greater than the working current the effective inductance becomes positive. This phase change is caused by the reversal of the capacitance currents between the two circuits.

FIG. 5—THE THREE IDEALLY SHIELDED RESISTORS

In computing the phase angles of the resistors the average effective inductance as measured at 500 and 60 cycles was used. In Table I the phase angles of the resistances at 60 cycles are given for the condition of equal potential drops along both working and guard resistances.

TABLE I

| Resistor ohms | Effective inductance mh | Phase angle $\theta$—sec | Tan $\theta$ radians |
|---|---|---|---|
| 10,000 | −0.06 | −0.47 | −0.0000022 |
| 5,000 | −0.02 | −0.31 | −0.0000015 |
| 1,000 | +0.005 | +0.39 | +0.0000019 |

The phase angle of each resistor is less than $10^{-5}$ radians. This is considerably larger than that found by calculation from the equations given in the appendix. This discrepancy can be explained by the fact that in the measurement all parasitic effects are taken into account, whereas in the mathematical analysis earth capacitance only is considered and no account taken of the self-inductance and self-capacitance. The equations given in the appendix show that the effect of earth capacitance in the ideally shielded resistors is reduced to the order of $10^{-15}$ radians. In the simple shielding scheme Fig. 3A, the effect of earth capacitance is much larger, being, roughly, $5 \times 10^{-6}$ radians.

The small phase angles of the ideally shielded resistors may be neglected and they may be regarded as pure resistances in even the most precise dielectric loss measurements of today.

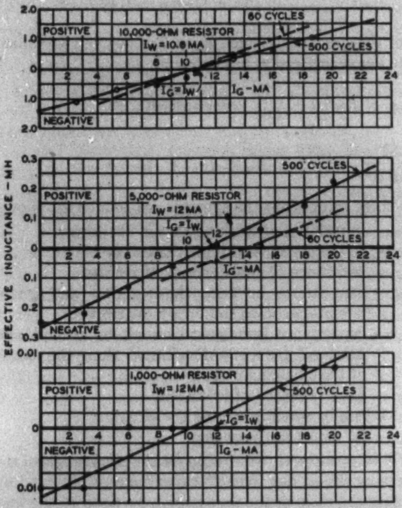

Fig. 6—Variation of Effective Inductance with the Variation of Current Through Shielding Coil

## The Standard of Low Power Factor

The combination of the shielded and guarded capacitor and an ideally shielded series resistor, therefore, forms a standard whose power factor can be computed accurately. The calculated values of the power factor of the standard at 60 cycles and the values of the resistances for equality of potential between main and guard electrodes of the capacitor are given in Table II.

TABLE II

| Resistor nominal value ohms | Working resistance $R_W$, ohms | Guard resistance $R_G$ ohms | Power factor of standard 60 cycles |
|---|---|---|---|
| 1,000 | 1,020 | 1,000 | 0.000195 |
| 5,000 | 5,106 | 5,000 | 0.000996 |
| 10,000 | 10,214 | 10,000 | 0.001993 |

## Checking of Schering Bridge

After the completion of the preliminary tests of the air capacitor and the resistors, the standard of low power factor was used to check the three Schering bridges in use in the Electrical Laboratories of The Johns Hopkins University. The results of tests on two of the bridges are given in Table III.

TABLE III

| Bridge | Voltage | Temp. | Gage pres. | P. F. |
|---|---|---|---|---|
| 1,000-Ohm Resistor | | | | |
| 1 | 1,000 | 22.9°C | 0 | 0.000196 |
| 2 | 3,000 | 21.2°C | 0 | 0.000194 |
| 2 | 5,000 | 22.8°C | 120 | 0.000196 |
| 2 | 10,000 | 22.5°C | 120 | 0.000193 |
| | | | Average | 0.000195 |
| 5,106-Ohm Resistor | | | | |
| 1 | 1,000 | 24.0°C | 105 | 0.000992 |
| 2 | 5,000 | 23.0°C | 107 | 0.000996 |
| 2 | 10,000 | 23.0°C | 107 | 0.000992 |
| 2 | 10,000 | 22.8°C | 100 | 0.000998 |
| 2 | 5,000 | 21.6°C | 175 | 0.001002 |
| 2 | 5,000 | 10.0°C | 100 | 0.000995 |
| | | | Average | 0.000996 |
| 10,214-Ohm Resistor | | | | |
| 1 | 1,000 | 24.0°C | 105 | 0.001983 |
| 2 | 5,000 | 23.0°C | 107 | 0.001993 |
| 2 | 10,000 | 23.0°C | 107 | 0.001997 |
| 2 | 5,000 | 22.8°C | 100 | 0.001990 |
| 2 | 10,000 | 22.8°C | 100 | 0.001986 |
| 2 | 5,000 | 10.0°C | 100 | 0.001997 |
| | | | Average | 0.001991 |

These tests were made at all three values of power factor of the standard. The average values of power factor given in Table III are almost in exact agreement with the computed values listed in Table II. In no case was a bridge found to be in error by as much as one per cent. It might well be mentioned here that it is quite remarkable that two Schering bridges which were built several years apart and which were of radically different arrangements should agree so closely.

The third bridge which was tested at 20 kv was found to be in error by a considerable amount. This bridge was carefully examined and cleaned. The principal source of error was discovered in an entirely unsuspected capacitance which was shunting one of its arms. Another source of trouble was found to be a capacitor whose calibration was in error. These defects were remedied and the calibration of the bridge for the range of the standard was then found to be correct.

## Conclusions

1. The standard of low power developed, consisting of a shielded and guarded capacitor and an ideally shielded resistor, represents satisfactorily a dielectric specimen.

2. Its capacitance is loss-free, and independent of variations in voltage, temperature and frequency.

3. Its resistance has a negligible phase angle and for practical purposes may be considered as a pure resistance.

4. Its values of capacitance and resistance may be determined accurately by independent measurements.
5. Its power factor and loss may be computed exactly.
6. Its value of power factor is independent of variations in applied voltage and temperature.
7. It possesses the primary requisite of a standard, namely permanence.

### ACKNOWLEDGMENT

The authors wish to take this opportunity to express their appreciation and thanks to Doctor F. B. Silsbee and Doctor F. K. Harris, both of the Bureau of Standards, for their assistance in this work.

## Appendix

### THEORETICAL RELATIONS

*Ideal Shielding.* In order to determine the effectiveness of the ideal method of shielding, the equivalent circuit of such a resistor was analyzed mathematically.

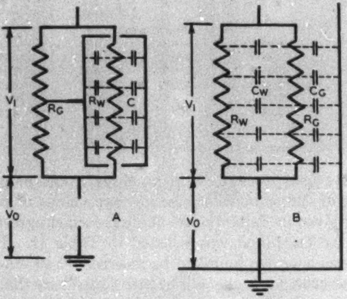

FIG. 7

A—EARTH CAPACITANCE SIMPLE SHIELD
B—EARTH CAPACITANCE IDEAL SHIELD

In this treatment the self-inductance and self-capacitance of the two coils were neglected. The distributed capacitance between the two coils and the distributed capacitance to earth of the shielding coil only were considered. The diagram of the equivalent circuit with the distributed capacitances indicated is given in Fig. 7B. The general case was treated where one end is at a fixed potential $V_0$ above ground and the other end at another fixed potential $(V_0 + V_1)$ above ground. This circuit is a special case of a transmission line or cable with uniformly distributed constants and thus Maxwell's equations apply.

In this treatment we are interested in finding an expression for the impedance of the working circuit. Since the derivation of the latter is rather lengthy and space limitations prohibit including it here, the final result only is given.

For the general mode of attack the reader is referred to Silsbee's[16] work, which treats a special case where one end of the resistance is grounded or $V_0 = 0$. The rigorous expression for the impedance involves a number of hyperbolic functions. Simplification was effected by expanding them into a rapidly converging power series which is easily analyzed. The first three terms of this series are:

$$Z_w = R_w \Bigg[ 1 - \left( \frac{7}{360} + \frac{15}{360} \frac{V_0}{V_1} \right) \omega^2 C_w C_G R_w R_G$$

$$+ j \left( \frac{31}{15{,}120} + \frac{63}{15{,}120} \frac{V_0}{V_1} \right) \omega^3 C_G C_W R_G R_W$$

$$(C_G R_G + C_W R_W + C_W R_G) + \ \ldots \Bigg]$$

For the special case when $V_0 = 0$ or one end grounded, the above expression becomes,

$$Z_{0W} = R_W \Bigg[ 1 - \frac{7}{360}\, \omega^2 C_W C_G R_W R_G +$$

$$\frac{31}{15{,}120}\, j \omega^3 C_G C_W R_G R_W (C_G R_G + C_W R_W + C_W R_G) + \ldots \Bigg]$$

In these expressions the symbols are defined as follows:

$Z_W$ = impedance of working circuit of resistor
$R_W$ = resistance of working circuit of resistor
$R_G$ = resistance of guard circuit of resistor
$C_W$ = capacitance between the working and guard circuits assumed uniformly distributed
$C_G$ = capacitance from guard circuit to ground also assumed uniformly distributed along the length of the shielding coil
$V_0$ = fixed potential of lower end
$V_1$ = rise in potential across the circuit
$\omega$ = $2\pi$ times the frequency

The approximate expression for the phase angle of the working circuit due to earth capacitance is obtained by taking the ratio of the first imaginary term to the first real term in the above series. Thus, for the special case of $V_0 = 0$, the phase angle at 60 cycles of the working circuit is,

$$\tan \theta_W \cong \theta_W$$

$$\cong \frac{31\, \omega^3 C_G C_W R_G R_W^2\, (C_G R_G + C_W R_W + C_W R_G)}{15{,}120\, R_W}$$

In order to simplify this expression, the assumption is made that $C_G$ is equal to $C_W$ which is entirely reasonable. Further, in the design of the resistor $R_G$ was made equal to $R_W$. The expression now reduces to

$$\theta_W \cong \frac{93\, \omega^3 C_W^3 R_W^3}{15{,}120}$$

The value of $C_W$ can be computed by use of the formula for the capacitance of a cylindrical capacitor. It was found to be approximately 15 $\mu\mu$f for the 10,000-ohm resistor. For a frequency of 60 cycles, the value of the phase angle due to earth capacitance alone for a 10,000-ohm resistor is

$$\theta_W \cong \frac{93 \times (377)^3 \times (15 \times 10^{-12})^3 \times (10^4)^3}{15{,}120}$$

$$= 1 \times 10^{-15} \text{ radians.}$$

This is the value of the phase angle for one end of the coil grounded. In most cases the resistance will be used with neither end grounded and thus it was necessary to determine what change this will introduce into the value of the phase angle. The series given above shows that the first imaginary term is a function of the ratio of the potentials at the ends of the coil. In order to simulate perhaps the worst case, the assumption is made that $V_0$ is equal to $V_1$, or that their ratio is unity. Now it is seen from the first of the two series, that this has the effect of increasing the imaginary component by a factor of three compared to the value which obtains when $V_0 = 0$. Hence also, the phase angle is increased by the same factor. Under these conditions, the phase angle due to earth capacitance for the 10,000-ohm resistor becomes $\theta_W \cong 3 \times 10^{-15}$ radians.

These theoretical relations show that the ideal method of shielding reduces the effect of earth capacitance to negligible values. The actual phase angle, determined experimentally, is considerably larger than that obtained by these computations. This is easily explained by the fact that the theoretical treatment does not take into account the effects of self-inductance and self-capacitance but only that of the earth capacitance. This method of shielding makes the effect of the latter so small that the effects of self-inductance and self-capacitance become large in comparison. These relations also indicate that the value of $V_0$ can be quite large compared to $V_1$ and yet the phase angle will be negligible. Thus, the ideal method of shielding effectively eliminates from consideration the most troublesome of the three parasitic properties of a resistor, namely earth capacitance.

*Simple Shielding.* For the purposes of comparison it was decided to determine the effect of earth or shield capacitance for a resistor shielded in the manner indicated in Fig. 7A. In obtaining the equation given below the assumption was made that the shield is at a potential equal to that of the midpoint of the resistor within it, or $\left(V_0 + \frac{V_1}{2}\right)$. Capacitance effects from shield to ground and guard circuit to ground were neglected since they are small compared to that of the shield capacitance.

The expression for the impedance of the equivalent circuit shown in Fig. 7A in terms of a power series is

$$Z_W = R_W\left(1 - \frac{1}{12} j\omega C R_W - \frac{1}{120}\,\omega^2 C^2 R_W^2 + \ . \ . \ . \right)$$

The expression for the phase angle of the working circuit is, therefore, $\tan\theta_W \cong \theta_W \cong \frac{1}{-12}\,\omega C R_W$

In order to make the basis of comparison the same $C$ was taken as 15 $\mu\mu$f which is the computed value for $C_W$ for the 10,000-ohm ideally shielded resistor. Thus, the phase angle at 60 cycles due to earth or shield capacitance for a 10,000-ohm resistor shielded as indicated in Fig. 7A is

$$\theta_W \cong -\frac{377 \times 15 \times 10^{-12} \times 10^4}{12} \cong -4.7 \times 10^{-6} \text{ radians}$$

Comparing this with the value obtained for the ideally shielded resistor it is seen that the latter is very much smaller. It will also be noted that for the simple shield the phase angle is negative and will add to the self-capacitance effects of the resistor; whereas in the ideally shielded case, the phase angle due to earth capacitance is positive and will tend to neutralize the self-capacitance. This shows further the effectiveness of the ideal method of shielding.

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## Discussion

For discussion of this paper see page 535.

# A Bridge for Precision Power-Factor Measurements on Small Oil Samples

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and

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AN extensive investigation of the power factor of cable oils and of pure synthetic hydrocarbons was started in June 1930 by the Cable Research Subcommittee of the National Electric Light Association, the work being carried on under the direction of Dr. V. Bush in the Electrical Engineering Research Laboratories of the Massachusetts Institute of Technology. The first step in the research was the design and construction of a suitable bridge for the measurement of power factors of the order of $10^{-4}$ to a precision of one per cent. The purpose of this paper is to describe the bridge and to present the problems involved in the design of a high-precision power-factor bridge. The complete mathematical theory of this bridge will be presented in a final report† to the Cable Research Subcommittee of the National Electric Light Association.

## I. CONSTRUCTION

A study of the various types of bridges showed that the Schering type may be satisfactorily adapted for high-precision power-factor measurements. However, the Schering bridge is not symmetrical; the high-tension arms contain the sample and a fixed condenser respectively, while one low-tension arm contains a resistance and the other a resistance and a variable condenser in parallel. To eliminate the effect of residual capacitances in the low-tension resistances it is necessary to have a variable condenser in one of the high-tension arms for capacitance balancing. Furthermore, the operating flexibility of the bridge is improved by having a symmetrical bridge, that is, similar low-tension arms.

A schematic diagram of the bridge is shown in Fig. 1. The high-tension arms of the bridge consist of a fixed air condenser $C_f$ in one arm and two variable condensers $C_v$ and $C_v'$ in the other arm. The sample $C_s$ can be connected in parallel with $C_v$.

A sectional view of the fixed condenser $C_f$ is shown in Fig. 2. The bridge cylinder is supported from the external shield cylinder by three fused quartz pillars located at each end of the bridge cylinder. This condenser is designed so that (a) a uniform electrostatic field is maintained over the length of the bridge or measuring section, (b) the bridge section is completely shielded, (c) a "grounded" ring is placed between the high-tension and shield sections to prevent leakage currents from entering the shield circuit, and (d) the small amount of solid dielectric is placed where it cannot influence the loss measured by the bridge. The condenser has a capacitance of approximately 86.8 $\mu\mu$f ($86.8 \times 10^{-12}$ farads) and a spacing of approximately 0.25 inch between plates.

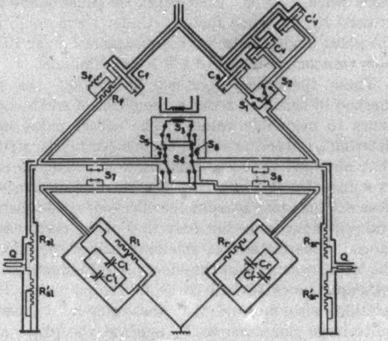

FIG. 1—SCHEMATIC DIAGRAM OF BRIDGE

| | |
|---|---|
| $C_f$ | Fixed condenser 86.8 $\mu\mu$f |
| $R_f$ | Fixed resistance |
| $S_f$ | Shield balancing resistance to compensate for *IR* drop thru $R_f$ |
| $C_v$ | Variable condenser 30-100 $\mu\mu$f |
| $C_v'$ | Variable condenser (Vernier) Approx. 2 $\mu\mu$f. Total change 0.066 $\mu\mu$f |
| $C_s$ | Sample |
| $S_1$, $S_2$ | Disconnecting switches |
| $S_3$, $S_4$ | Reversing switches |
| $S_5$, $S_6$ | Shield balancing switches |
| $R_l$, $R_r$ | Leeds and Northrup precision resistances 0.0—9,999.9 ohms |
| $C_l$, $C_r$ | General Radio precision condensers 1,500 $\mu\mu$f |
| $C_l'$, $C_r'$ | General Radio mica condensers 0—0.1 $\mu$f |
| $R_{sl}$, $R_{sr}$ | Shield balancing resistances (voltage) 0—15,000 ohms |
| $R_{sl}'$ $R_{sr}'$ | Shield balancing resistances (phase) 0—2 ohms |
| Q, Q | 100,000 ohms in series with quadrature voltage |
| $S_7$, $S_8$ | Switches for making single or double shield. Normally closed |

The variable condenser $C_v$ is shown in section in Fig. 3. Small changes in capacitance can be obtained by an axial movement of the inner cone by means of an accurate thread cut on the shaft. Condenser $C_v$ is the larger of the variable condensers and can be varied from approximately 30 $\mu\mu$f to 100 $\mu\mu$f by a 5-inch movement of the internal cone or 200 revolutions of the shaft. Condenser $C_v'$ is similar to $C_v$ and is variable from approximately 1.96 $\mu\mu$f to 2.02 $\mu\mu$f by a 1½-inch movement of the inner cone or 60 revolutions of the

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†Progress reports covering the design and construction were presented at periodic intervals to the Cable Research Subcommittee of the National Electric Light Association. A preliminary paper, not published, describing this bridge was presented by the authors at the meeting of the Insulation Committee of the National Research Council at Harvard University in November, 1931.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

shaft. The shafts are rotated by means of a crank carried on the operating panel of the bridge. The shafts also carry graduated disks five inches in diameter with one hundred scale divisions and geared Veeder counters to permit accurate readings of the condenser settings. Backlash is prevented by the use of a simple lash lock.

In the low-tension arms, $C_l$ and $C_r$ may be varied through a range of 1,500 $\mu\mu$f by twenty-five revolutions of a crank located on the operating panel of the bridge. This crank carries a graduated dial with one hundred scale divisions and thus one scale division represents 0.6 $\mu\mu$f.

The resistances $Q$ are connected to the primary side of the transformer supplying the bridge voltage. Thus a voltage is obtained across $R_{sl}'$ and $R_{sr}'$ which is in approximate time quadrature with the voltage across $R_{sl}$ and $R_{sr}$ and thereby permits of both phase and magnitude adjustment of the shield voltage.

Circuit connections of the bridge are controlled by switches $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, and $S_6$. Switches $S_1$ and $S_2$ are used in obtaining power-factor measurements by means of a substitution method. Switch $S_1$ connects sample $C_x$ to either the bridge or shield, while switch $S_2$ performs a similar service for $C_s$ and $C_s'$. Switch $S_3$ reverses the connections to the input transformer of the amplifier and galvanometer. Switches $S_5$ and $S_6$ connect the detecting circuit either between bridge and shield or between the diagonal points of the bridge. Switch $S_4$ reverses the low-tension arms of the bridge.

The detecting circuit consists of an input transformer, the shield of the primary winding being at shield potential, while the shield of the secondary winding is at ground potential, a three-stage pushpull amplifier, a band-suppression filter, 57-63 cycles per second, two low-pass filters, 0 to 80 cycles per second, a two-stage amplifier and a vibration and an alternating-current galvanometer. The bridge normally is operated at a frequency of 55 cycles per second. Thus the filter will eliminate the 60-cycle pick-up from other electrical machinery and also prevent harmonics from influencing the measurements. The alternating-current galvanometer is a Leeds and Northrup No. 2470 with a sensitivity of 0.025 microamperes per millimeter deflection.

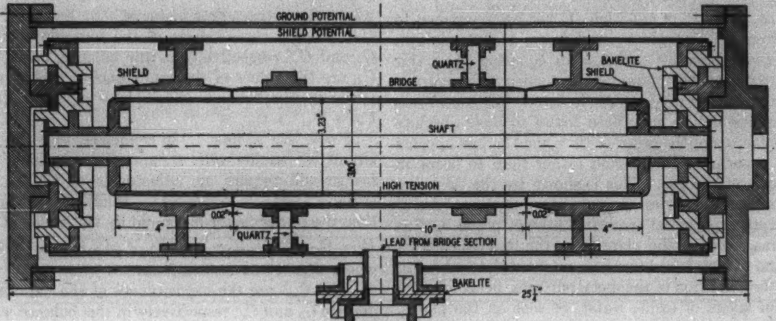
GROUND POTENTIAL
SHIELD POTENTIAL
SHIELD
QUARTZ
BRIDGE
BAKELITE
SHIELD
SHAFT
3.23"
3.90"
HIGH TENSION
0.02"
0.02"
4"
QUARTZ
10"
4"
LEAD FROM BRIDGE SECTION
BAKELITE
25¼"

FIG. 2—FIXED CONDENSER

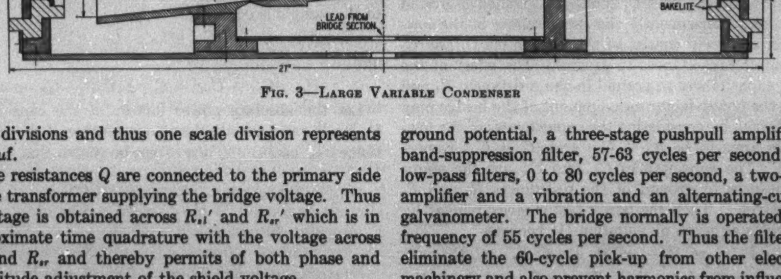
SHIELD POTENTIAL
SHIELD
5½"
0.02"
QUARTZ
10"
QUARTZ
5½"
BRIDGE SECTION
0.02"
GROUND POTENTIAL
HIGH TENSION
SHIELD
SHAFT
1.40"
0.75"
THREADED SHAFT 40 THREADS PER INCH
5.60"
4.25"
BAKELITE
8½"
LEAD FROM BRIDGE SECTION
27"

FIG. 3—LARGE VARIABLE CONDENSER

The bridge is designed for a maximum voltage of 5,000 volts.

## II. POWER-FACTOR MEASUREMENTS

The power factor measured by the bridge is

$$P_f - P_x = \omega C_r R_r - \omega C_l R_l \qquad (1)$$

in which $P_f$ and $P_x$ are respectively the absolute power factors of the fixed condenser $C_f$ and combination of condensers in the arm containing $C_v$. Thus to obtain the power factor of an oil sample to a precision of $10^{-6}$ requires the evaluation of the absolute power factor of $C_f$ and $C_v$ to the same precision.

In the past, $P_f$ of equation (1) has been assumed to be zero and the absolute power factor of the unknown has been arbitrarily taken as in equation (1). Our measurements show, however, that when high accuracy is desired such a procedure is in error. Air condensers of the best design have been found to have absolute power factors of the order of $10^{-5}$, and the loss appears to be a surface phenomenon rather than to occur in the body of the gas. This is shown by the following results: the loss varies approximately as the square of the average potential gradient between plates and as the first power of the plate area; the loss depends on the kind of metal used for the condenser plates and also upon the condition of the metal surfaces, being affected by thin layers of oxide, water, or soot on the plates. However, all of the loss does not occur in the metal itself or in the oxide coating since the power factor changes as the air pressure is changed. Furthermore, the power factor is affected by the temperature of the condenser and is reduced by degassing of the condenser surfaces. A more detailed discussion of the absolute power factor of air condensers will be given in a forthcoming paper.

In determining the values of $\omega RC$ in equation (1), obviously the values of $\omega$ and $R$ may be obtained to the desired precision. However, the value of the capacitance in either low-tension arm is more difficult to determine. As shown in Fig. 1 the resistances $R_r$ and $R_l$ and the capacitances $C_r$ and $C_l$ are shielded at ground potential. Consequently the capacitances in the low-tension arms will consist of the condensers $C_r$ and $C_l$ and shunt capacitances to ground. The effect of the shunt capacitances to ground in the resistances $R_l$ and $R_r$ on the power-factor measurement of the bridge may be obtained by considering the capacitances of the low-tension arms to be $(C_l + C_{ls})$ and $(C_r + C_{rs})$ respectively. The capacitances $C_{ls}$ and $C_{rs}$ are the shunt capacitances to ground of the resistances $R_l$ and $R_r$ respectively. Then the power-factor measurement by the bridge as given by equation (1) becomes

$$P_f - P_x = \omega C_r R_r - \omega C_l R_l + \omega C_{rs} R_r - C_{ls} R_l \qquad (2)$$

Equation (2) shows that effect of $C_{rs}$ and $C_{ls}$ on the power-factor measurement by the bridge depends upon their difference. This effect may be decreased by using identical construction and mounting for the two low-tension arms, and by using equal values or $R_l$ and $R_r$. It is also helped by using low values of resistances $R_l$ and $R_r$. However, this will decrease the sensitivity of the bridge.

The effect of $C_{rs}$ and $C_{ls}$ on the power factor measured by the bridge may be eliminated by using a substitution method. Thus in Fig. 1 the bridge is first balanced with the sample $C_s$ connected to the shield by the switch $S_1$. With the bridge arms connected direct and $R_r$ equal to $R_l$, the power factor measured by the bridge is

$$P_f - P_{x1} = \omega C_{r1} R_r - \omega C_{l1} R_l + \omega C_{rs} R_r - \omega C_{ls} R_l \qquad (3)$$

where $P_{x1}$ is the power factor of $(C_{v1} + C_{v1}')$, $C_{v1}$ and $C_{v1}'$ are the capacitances of the variable condensers $C_v$ and $C_v'$ respectively in this balance, and $C_{r1}$ and $C_{l1}$ are the values of the condensers $C_r$ and $C_l$ respectively in this balance. Since $R_l$ is equal to $R_r$, then $C_{v1} + C_{v1}' = C_f$.

If now the sample $C_s$ is connected into the bridge circuit in parallel with $C_v$ and $C_v'$, rebalance of the bridge will require an adjustment of $C_{v1}$, $C_{v1}'$ and either $C_{r1}$ or $C_{l1}$. Assuming $C_{l1}$ is adjusted for balance, then the power factor measured by the bridge is

$$P_f - P_{x2} = \omega C_{r1} R_r - \omega C_{l2} R_l + \omega C_{rs} R_r - \omega C_{ls} R_l \qquad (4)$$

where $P_{x2}$ is the power factor of $(C_{v2} + C_{v2}' + C_s)$, $C_{v2}$ and $C_{v2}'$ are the capacitances of the variable condensers $C_v$ and $C_v'$ respectively in this balance, and $C_{l2}$ is the new value of $C_l$ to obtain balance. In this balance $(C_{v2} + C_{v2}' + C_s) = C_f$.

Subtracting equations (4) and (3) gives

$$P_{x2} - P_{x1} = \omega R_l (C_{l2} - C_{l1}) \qquad (5)$$

Equation (5) shows that the difference in power factors $P_{x2} - P_{x1}$ is independent of the phase angle of the resistances $R_r$ and $R_l$ and depends only upon difference in the capacitance readings of one of the low-tension condensers in the two balances. However, $P_{x2}$ and $P_{x1}$ are power factors of combination of capacitances in the variable high-tension arm of the bridge. It is desired to evaluate the absolute power factor of the sample $P_s$ from equation (5). The capacitance $C_s$ of the sample is equal to

$$C_s = (C_{v1} + C_{v1}') - (C_{v2} + C_{v2}') = C_f - (C_{v2} + C_{v2}') \qquad (6)$$

and

$$C_f = C_{v1} + C_{v1}' = C_{v2} + C_{v2}' + C_s \qquad (7)$$

Let the absolute power factors of the capacitance $C_{v1}$ be $P_{v1}$ and the absolute power factor of the capacitance $C_{v1}'$ be $P_{v1}'$. Then it can be shown that

$$P_{x1} = (P_{v1}) \frac{C_{v1}}{C_f} + (P_{v1}') \frac{C_{v1}'}{C_f} \qquad (8)$$

and

$$P_{x2} = (P_{v2}) \frac{C_{v2}}{C_f} + (P_{v2}') \frac{C_{v2}'}{C_f} + (P_s) \frac{C_s}{C_f} \qquad (9)$$

in which $P_{v2}$ is the absolute power factor of the capacitance $C_{v2}$ and $P_{v2}'$ is the absolute power factor of the capacitance $C_{v2}'$. In general the difference between the capacitance $C_{v1}'$ and $C_{v2}'$ to obtain balance is quite small so that the difference between

$$P_{v1}' \frac{C_{v1}'}{C_f} \text{ and } P_{v2}' \frac{C_{v2}'}{C_f}$$

is negligible. Then the difference between equations (**9**) and (**8**) is

$$P_{x2} - P_{x1} = (P_{v2}) \frac{C_{v2}}{C_f} - (P_{v1}) \frac{C_{v1}}{C_f} + P_s \frac{C_s}{C_f} \qquad \textbf{(10)}$$

Equating (**5**) and (**10**) and solving for $P_s$ gives

$$P_s = \frac{\omega R_l C_f}{C_s} (C_{l2} - C_{l1}) - P_{v2} \frac{C_{v2}}{C_s} + P_{v1} \frac{C_{v1}}{C_s} \qquad \textbf{(11)}$$

The use of the variable condenser in one of the high-tension arms of the bridge permits obtaining a capacitance balance of the bridge when the sample is connected into the bridge circuit by adjusting the variable capacitance instead of the resistances $R_r$ or $R_l$. Thus, it is only necessary to determine the differences in capacitance settings of either $C_l$ or $C_r$. The capacitances $C_l$ or $C_r$ may be calibrated against a standard condenser or as shown in Part V may be calibrated in terms of known power factors.

The precision in power-factor measurement by the bridge is thus dependent upon the accuracy with which the changes in $C_l$ or $C_r$ can be determined. The use of variable high-tension condensers makes it necessary to determine only the difference in the absolute values of different settings of either $C_l$ or $C_r$ instead of absolute values for each setting. For increased precision it would be possible to use a variable condenser of the type shown in Fig. 3 with dimensions such that differences in capacitances for different settings could be obtained to the desired accuracy from the dimensions of the condenser.

## III. Sensitivity of the Bridge

A theoretical treatment of the sensitivity of the bridge has been made by Tschiassny.[12] Defining the sensitivity of the bridge $S_b$ as the reciprocal of the smallest detectable loss angle $\Delta\delta_x$, the sensitivity is

$$S_b = \frac{1}{\Delta\delta_x} = \frac{E}{\Delta e_m} \frac{\omega C_f R_r Z_g}{[(R_l + R_r + R_g)^2 + (\omega L_g)^2]^{1/2}} \qquad \textbf{(12)}$$

in which $\Delta e_m$ is the smallest voltage that can be detected when applied across the input terminals of the amplifier, $E$ is the applied bridge voltage, and $Z_g$, $R_g$ and $L_g$ are the input impedance, resistance and inductance respectively of the amplifier. Thus the sensitivity of the bridge is (a) increased by increase in frequency, (b) inversely proportional to $\Delta e_m$, (c) directly proportional to the applied voltage $E$, (d) directly proportional to the capacitance in the high-tension arms, (e) nearly directly proportional to the low-tension resistances $R_r$ and $R_l$, (f) increased by an increase in the input impedance of the amplifier until $Z_g$ becomes large relative to $(R_l + R_r)$.

The value of $\Delta e_m$ for this bridge may be adjusted to $10^{-8}$ volts. This will give (with $R_l$ and $R_r$ equal to 10,000 ohms, $C_f$ equal to 86.8 μμf, $R_g$ equal to 1,500 ohms, $L_g$ equal to 65 henrys, frequency of 60 cycles and an applied bridge voltage of 1,000 volts) a bridge sensitivity expressed in power factor of approximately $4 \times 10^{-8}$.

## IV. Oil Cell

One type of oil cell that has been developed for this research is shown in Fig. 4. This cell consists principally of high-voltage, measuring and shield cylinders similar to the fixed and variable condensers shown in Figs. 2 and 3. These cylinders are made of nickel. The use of shield cylinders assures an approximately uniform

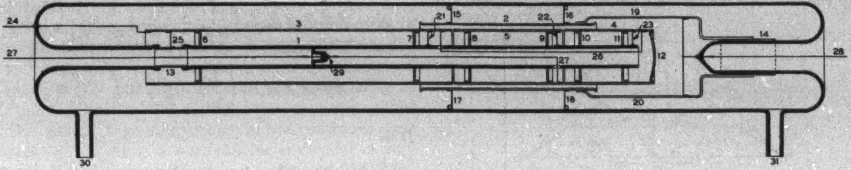

Fig. 4—Oil Cell

1. Pyrex glass
2. High-tension section—nickel cylinder
3, 4. Shield section—nickel cylinders
5. Measuring section—nickel cylinder
6—11. Supports—nickel disks
12. Shield—nickel disk
13. Metal shield sealed into glass tube
14. Support for high-tension section 2
15—18. Supports for high-tension section 2
19, 20. Nickel wire supports for high-tension section
21, 23. Spacers for shield sections
22. Spacer for measuring section
24. Lead from shield sections 3, 4 and 13
25. Connection from shield 13 to shield 3
26. Connection from shield 3 to shield 4
27. Lead to measuring section 5
28. Lead to high-tension section 2
29. Seal for measuring-section lead

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[12] See bibliography for numbered references.

field in the oil under test and also permits the desired precision in power-factor measurement to be obtained. The use of metal cylinder 13 sealed into the glass tube and connected to shield prevents the glass-conduction and surface-leakage currents from the high-tension lead 26 from entering the bridge circuit and being measured with the power factor of the oil. The cell is designed so that it can be thoroughly evacuated. A coil is mounted around the outer glass tube 1 so that the nickel cylinders may be heated by induction and a gas-free surface obtained. Also the cell is mounted in an oven to permit heating the cell. It is planned to use this cell for tests on pure synthesized hydrocarbons. Some evidence has already been obtained which would indicate that surface effects in the cell have an appreciable influence on the measured power factor of commercial cable oil.

## V. TESTS OF POWER-FACTOR MEASUREMENTS OF THE BRIDGE

One check on the operation of the bridge is obtained by connecting a resistance $R_f$ in series with the measuring section of the fixed condenser $C_f$. In this way the power factor of the fixed condenser is increased by $\omega R_f C_f$. Installing the resistance $R_f$ in series with the fixed condenser requires an alteration of the shield circuit as shown in Fig. 1. The current flowing through the capacitance $C_f$ will also flow through $R_f$, thereby introducing a voltage drop in the bridge circuit. A corresponding voltage drop must be introduced into the shield circuit by the use of $S_f$ so that the bridge circuits on both sides of the resistance $R_f$ will be completely shielded. The value of $S_f$ is obtained by connecting the galvanometer between bridge and shield by means of switches $S_5$ and $S_6$ in Fig. 1 and then adjusting $S_f$ until the galvanometer shows no deflection when the bridge and shield are connected together on the condenser side of the resistance $R_f$.

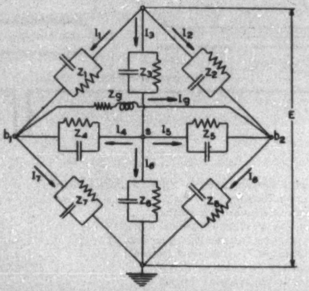

FIG. 5—EQUIVALENT BRIDGE CIRCUIT

The substitution method is used in measuring the increase in power factor of the fixed condenser due to connecting the resistance $R_f$ in series with $C_f$. The bridge is first balanced with $R_f$ equal to zero and then balanced with a definite value of $R_f$ and the change in either $C_t$ or $C_r$ obtained. A number of tests have shown that the measured power factor is well within the desired precision of $10^{-6}$.

## VI. SHIELD BALANCE

A diagrammatic plan of this bridge is shown in Fig. 5. In this diagram "$s$" represents the shield, $Z_4$ and $Z_5$ represent the impedances between the shield and bridge points $b_1$ and $b_2$ respectively, $Z_3$ represents the capacitance from high tension to shield and $Z_6$ represents an impedance for magnitude-balancing and phase-balancing the potential of "$s$" with respect to $b_1$ and $b_2$. Solving for the galvanometer current[28] from Fig. 5 gives

$$\frac{I_g}{E} = \frac{N}{D} \tag{13}$$

where

$$N = Z_1Z_8Z_3Z_4Z_5Z_6\left(\frac{Z_2}{Z_3Z_5}+\frac{Z_7}{Z_4Z_6}+\frac{1}{Z_3}+\frac{1}{Z_4}+\frac{1}{Z_5}+\frac{1}{Z_6}\right)$$

$$- Z_2Z_7Z_3Z_4Z_5Z_6\left(\frac{Z_1}{Z_3Z_4}+\frac{Z_8}{Z_5Z_6}+\frac{1}{Z_3}+\frac{1}{Z_4}+\frac{1}{Z_5}+\frac{1}{Z_6}\right)$$

$$D =$$

$$-\left\{Z_3Z_4Z_5Z_6\left(\frac{1}{Z_3}+\frac{1}{Z_4}+\frac{1}{Z_5}+\frac{1}{Z_6}\right)\Big[Z_1Z_2\,(Z_7+Z_8+Z_g)\right.$$

$$+ Z_7Z_8(Z_1 + Z_2 + Z_g) + Z_g(Z_1Z_8 + Z_2Z_7)\Big]$$

$$+ Z_2Z_3Z_4Z_6Z_8Z_g(Z_1 + Z_7)\left(\frac{1}{Z_3} + \frac{1}{Z_4} + \frac{1}{Z_6}\right)$$

$$+ Z_1Z_3Z_5Z_6Z_7Z_g(Z_2 + Z_8)\left(\frac{1}{Z_3} + \frac{1}{Z_5} + \frac{1}{Z_6}\right)$$

$$\left. + Z_1Z_2Z_7Z_8(Z_3 + Z_6)\,(Z_4 + Z_5 + Z_g)\right\}$$

Equation (13) shows that the bridge is balanced, (that is, $\frac{I_g}{E}$ is zero), for the condition of

$$Z_1Z_8 = Z_2Z_7 \tag{14}$$

and

$$Z_1Z_6 = Z_3Z_7 \tag{15}$$

or

$$Z_2Z_6 = Z_3Z_8 \tag{16}$$

For the relative impedances in this bridge and for the condition of the shield close to balance, the value of $\frac{I_g}{E}$ as a function of $Z_2$ and $Z_1$ and as given by (13) may be closely approximated by

$$\frac{I_g}{E} \cong \left[\frac{Z_2 - Z_1}{Z_1 Z_2}\right]\left[\frac{Z_7}{2Z_7 + Z_g}\right] \tag{17}$$

For the relative values of impedances in this bridge and for the condition of equal ratio arms and the bridge circuit in balance (that is, $Z_1 Z_8 = Z_2 Z_7$) the value of $\frac{I_g}{E}$ as a function of $Z_6$ and as given by (13) may be closely approximated by

$$\frac{I_g}{E} \cong \left[\frac{Z_6}{Z_3} - \frac{Z_7}{Z_1}\right]\left[\frac{Z_7}{2Z_7 + Z_g}\right]\left[\frac{1}{Z_4} - \frac{1}{Z_5}\right] \tag{18}$$

Equation (18) shows that with the bridge circuit balanced and the shield circuit unbalanced, the galvanometer current is proportional to the magnitude or phase unbalancing of the shield and is also proportional to the difference in the admittances between bridge and shield circuit. Thus the closeness with which $Z_6$ must be adjusted for a given precision in power-factor measurement depends directly upon the difference of the capacitances between the bridge and shield circuits. Furthermore it may be noted from a comparison of equations (17) and (18) that with the power factor of $Z_4$ and $Z_5$ equal to zero, a magnitude-unbalance of the shield circuit, that is, a change in the resistance component of $Z_6$, will give a galvanometer current of very nearly the same phase position as a power factor unbalance between $Z_2$ and $Z_1$ with the bridge and shield previously balanced. Similarly a phase unbalance of the shield circuit from balance with the power factor of $Z_4$ and $Z_5$ equal to zero will give a galvanometer current of the same phase position as a capacitance unbalance between $Z_2$ and $Z_1$ with the bridge and shield previously balanced.

Kouwenhoven and Baños[27] have stated that it is advisable to keep the cross-capacitances existing between the measuring and guard circuits low, and also that it is of great importance that the conductances of the cross-capacitances be maintained at zero. However, it should be noted that it is the difference in the cross-capacitances which is of importance to keep small and not their individual magnitudes. Kouwenhoven and Baños[27] have also stated that for the relative impedances in their bridge that phase balancing of the shield is not necessary. This predicates, however, that the phase shifter for bridge balancing must be quite accurately set.

The effect of magnitude and phase unbalancing of the shield circuit with the bridge circuit balanced is shown graphically in Fig. 6. The current $I_p$ shown in Fig. 6 is the galvanometer current per unit bridge voltage for the condition of $Z_1$, $Z_3$, $Z_7$, $Z_8$ as given in Fig. 6 and $Z_2$ equal to 100 $\mu\mu$f and a power factor of $10^{-6}$ and $Z_6$ equal to 5,000 ohms in parallel with 300 $\mu\mu$f. Thus it represents the condition of a power factor unbalance in $Z_2$ and $Z_1$ of $10^{-6}$ with the bridge and shield previously balanced. The current $I_c$ represents a capacitance unbalance of $10^{-4}$ $\mu\mu$f in $Z_2$ and $Z_1$, the remaining conditions being the same as for $I_p$.

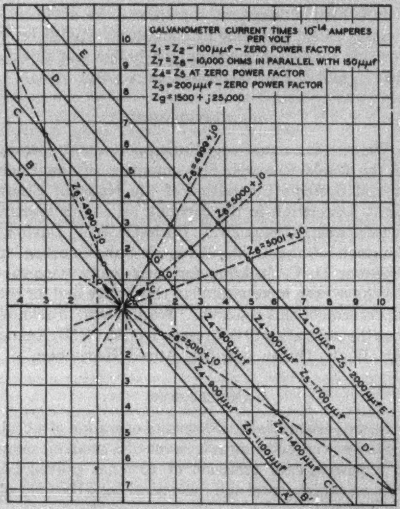

Fig 6—Galvanometer Current for Shield Unbalancing

Current $OO'$ in Fig. 6 represents the galvanometer current in magnitude and phase for $Z_1$, $Z_2$, $Z_3$, $Z_7$, $Z_8$ and $Z_g$ as given in Fig. 6, $Z_4$ and $Z_5$ are equal to impedances corresponding to 600 $\mu\mu$f and 1,400 $\mu\mu$f at zero power factor respectively and $Z_6$ is equal to 4,999 + $j$0. Thus with the bridge circuit balanced and the shield circuit unbalanced in magnitude and in phase the galvanometer current $OO'$ has a component in phase with $I_p$ and $I_c$ and therefore represents an indicated power factor and capacitance difference between $Z_2$ and $Z_1$. For the same conditions except for $Z_6$ equal to 5,000 + $j$0 the galvanometer current is given by $OO''$ and in this case the galvanometer current represents a capacitance difference between $Z_2$ and $Z_1$. With the capacitances between the shield and bridge ($Z_4$ and $Z_5$) having a power factor other than zero the slope of the lines $AA'$, $BB'$, $CC'$, $DD'$ and $EE'$ in Fig. 6 would be changed by approximately the angle of $Z_4$ and $Z_5$. Thus in this case a phase unbalance of the shield will give a galvanometer current with a component in phase with $I_p$, and therefore the bridge would have an indicated power factor although the bridge circuit is balanced. With the bridge constants as given in Fig. 6 the shield is unbalanced in phase by 300 $\mu\mu$f. In the usual bridge the difference between the shield capacitance to ground and the capacitance from bridge points $b_1$ and $b_2$ to ground may be many times this value. This difference in capacitance in combination with a difference between $Z_4$ and $Z_5$ and a power factor of 1 to 2 per cent of $Z_4$ and $Z_5$ can give a power-factor indication in the galvanometer even with the bridge circuit balanced, of several times $10^{-6}$. These results have been checked from the rigorous equation (**13**) and also by experiment.

Another factor of importance in shield balancing is the accuracy with which the phase shifter can be set in the bridge balance. The accuracy of the setting will depend upon the sensitivity of the bridge and the design of the phase shifter. This factor in addition to the effect of difference between $Z_4$ and $Z_5$ makes it advisable to balance the shield for phase when measuring to a precision in power factor of $10^{-6}$.

It is further suggested that it may be advisable to simplify shield balancing by connecting into the bridge, variable condensers between the bridge and shield so that $Z_4$ and $Z_5$ may be made approximately equal.

### ACKNOWLEDGMENT

We wish to acknowledge the support and cooperation of the Cable Research Subcommittee of the Underground Systems Committee of the National Electric Light Association in the carrying on of this research. We also wish to thank Dr. V. Bush, Dr. W. F. Davidson, chairman of the Cable Research Subcommittee and Professor D. C. Jackson, for their many suggestions that have been incorporated in this bridge and for their supervision of this research. We also wish to acknowledge the association in this research of Mr. N. D. Kenney, Mr. W. R. Oppen and Mr. Alfred Herzenberg.

### CONCLUSIONS

Our experience in the design and operation of a bridge for the power-factor measurement of a small oil sample to a power-factor precision of $10^{-6}$ has proved both from an experimental and theoretical basis the following conclusions:

1. Air condensers of usual design may have absolute power factors substantially higher than $10^{-6}$.

2. The measurement of the power factor of an oil sample to a power-factor precision of $10^{-6}$ requires the evaluation of the absolute power factor of the high-tension condensers forming a part of the bridge to a power-factor precision of $10^{-6}$.

3. The use of high-tension variable condensers for capacitance balancing eliminates the necessity of determining absolute values of capacitance of the power-factor measuring condensers.

4. With a single shield circuit, the difference in capacitance between the bridge and shield on the two sides of the bridge determines the accuracy to which the shield must be balanced.

5. It is suggested that variable condensers be installed between bridge and shield circuits so that the difference in capacitance in (4) can be made quite small.

6. The sensitivity of the bridge expressed in terms of power factor should be substantially higher than the desired power-factor precision.

7. The use of ordinary insulations between bridge and shield, the limit in accuracy to which the phase shifter can be set, and relatively large differences in capacitance between bridge circuits and shield, make it necessary to provide phase balancing of the shield circuit.

8. Ordinary insulations may be used between the bridge and shield circuits.

9. The insulation between bridge and shield circuits should be effectively shielded from the high-tension sections.

10. Insulation of shield and high-voltage sections should be to ground.

11. It is suggested that the power-factor measuring condensers be so designed that differences in absolute capacitances may be obtained from dimensions.

12. The power-factor measurement of oil samples to a power-factor precision of $10^{-6}$ requires a study of surface effects in the oil cell and the method of preparing the oil cell for the sample.

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## Discussion

### A STANDARD OF LOW POWER FACTOR

(KOUWENHOVEN AND BERBERICH)

### A BRIDGE FOR PRECISION POWER FACTOR MEASUREMENTS

(BALSBAUGH AND SPORN)

**E. S. Lee:** The papers on power factor bridges and reference standards largely trace their A.I.E.E. history back to the year 1925, for in that year there was a paper presented on the testing of cables,[1] which, as far as I can ascertain, was the first A.I.E.E. paper to describe the use of the Schering bridge. That bridge was used for the measurement of cable samples and long lengths at power factor values in the order of 0.005 (0.5 per cent) and results are given in the paper to show that by independent methods the values were in agreement within power factor 0.002 or (0.2 per cent).

Immediately thereafter Schering and other bridges sprang into existence. Between then and today about a dozen papers have been published in the TRANSACTIONS of the Institute, each successive paper showing advance, until today we have the paper by Messrs. Balsbaugh and Moon, stating as their objective a power-factor bridge for the measurement of power factor in the order of 0.0001 (0.01 per cent) to a precision of 0.000001. I take it from the paper that the authors achieved the desired precision, though the attainment of an accuracy figure is not made clear.

The standard described by Messrs. Kouwenhoven and Berberich fills a desired need. It recalls the many things we have done to assure ourselves of the accuracy of our bridges. Comparison of values obtained by others—the use of a calorimeter, measurement by independent methods—all of which have been desired, make a standard of reference very desirable. We wish we might have availed ourselves of the opportunity to use the Kouwenhoven and Berberich standard in measurements with our own bridges, but present conditions have prevented this, as the shipping and packing of such represents a sum which in these days is considered substantial. The usefulness of such a standard is increased considerably if it may easily and cheaply be shipped as a piece of cable, or carried by hand as the standard developed by Mr. Farmer and referred to by Messrs. Kouwenhoven and Berberich.

**J. C. Balsbaugh:** It should first be appreciated that connecting a resistance in series with a condenser increases the power factor of the combination of condenser and resistance by a known amount but does not give any indication of the absolute power factor of the combination. The absolute power factor of the combination is represented by the resistance only when the absolute power factor of the condenser is zero or negligible within the desired precision range. A research project carried on in the Electrical Engineering Department of the Massachusetts Institute of Technology in cooperation with the Cable Research Subcommittee of the National Electric Light Association, involving the study of the power factor of small oil samples with a bridge having an accuracy and precision equal to $10^{-6}$ and a sensitivity that may be adjusted to $10^{-8}$ has shown conclusively that air condensers have absolute power factors which have been found to be as high as $10^{-4}$ and are a function of kind of metal surfaces, voltage gradient and nature of the surfaces.

The method of connecting a resistance in series with a condenser to increase the power factor by a known amount has been used by the writer for several years as a means of checking the calibration of the power-factor measuring condensers. This has been done for power factor ranges of 3 to 5 times $10^{-6}$ and where the accuracy of the shield balance and the dimensions of shielding for the resistance are such that it can be shown that it is not necessary to use an "ideally" shielded resistance.

It can be shown that both the precision and accuracy of a power-factor measurement can quite simply and easily be obtained to a value of $10^{-6}$ and beyond by (a) accurate bridge balancing using a variable high-tension condenser, (b) accurate shield balancing, (c) proper condenser design, (d) measuring power factor in terms of differences in capacitances of one low-tension condenser for different settings through reversal of low-tension arms and use of equal ratio arms with fixed low-tension resistances, (e) evaluation of absolute power factors of high-tension condensers to desired range and (f) use of a proper bridge circuit.

Kouwenhoven and Berberich have made a very interesting design of a condenser and an ideally shielded resistance. However, it should be appreciated that it cannot be used as a standard of power factor in a range where the absolute power factor of the condenser is significant. Even when used in a range where it may justifiably be used as a standard I believe that equal precision and accuracy may be obtained more easily and economically through the use of a proper bridge circuit and a proper method of bridge operation and measurement.

**W. B. Kouwenhoven:** The standard we have constructed is heavy and bulky to ship because in a single unit it embraces both the air capacitor and the ideally shielded resistor. The capacitor like all high voltage air capacitors is necessarily large and heavy. The ideally shielded resistor, however, is small and light and could be easily shipped if desired. It may be used with any air capacitor whose main and guard plates have equal capacitances. In case an air capacitor has a low guard capacitance compared to the main plate, it may be brought up to the one-to-one ratio by connecting a second air capacitor of the proper value in parallel with the guard.

As Mr. Balsbaugh points out, the simple act of connecting a resistance in series with an air capacitor only gives a known increase in power factor but does not tell anything about the absolute value of that quantity. If, however, the capacitor is constructed of the proper metal, is polished, cleaned with alcohol and is operated at low voltage gradients and in a dry atmosphere kept free from dust, its power factor is zero at commercial frequency to within the accuracy of our present day measuring equipment. It is true that there is even then a certain loss caused by the ionization of the air due to radium emanations from the earth and to other sources of ionization. This might be called the inherent power factor of an air capacitor. Its value is very small and Doctor Lemmon and I were not able to detect the ionization current in any of our capacitors at The Johns Hopkins University, using a high voltage continuous current supply and a galvanometer with a sensitivity of $10^{-11}$ amperes per millimeter deflection. If the air capacitor surfaces become tarnished and dust collects on them the power factor is no longer unity. In the limited space in our paper we have pointed out some of the errors that may be introduced by the introduction of a simple series resistance in the air capacitor lead as suggested by Mr. Balsbaugh. We do not recommend this method as the difference of potential between the main and guard leads that results causes a flow of current through the capacitance existing between them. And even if the guard and main lead are brought to the same potential and phase at the bridge corner by means of Mr. Balsbaugh's bridge arrangements that does not mean that they are at the same potential throughout their entire length.

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[1] *Testing High-Tension Impregnated Paper-Insulated, Lead-Covered Cable*, by E. S. Lee, A.I.E.E. TRANS., 1925, p. 105.

# Laboratory Measurement of Impulse Voltages

BY J. C. DOWELL* and C. M. FOUST†
Associate, A.I.E.E. Member, A.I.E.E.

***Synopsis***—*A brief description is given of impulse generators and the discharge circuit constants involved in obtaining impulse voltages of the desired wave shapes. The relative influences of these constants are recognized and simplified discharge circuits are given. The variations in the wave shape and the reasons for the differences in sparkover values obtained with the three test waves, ½/5, 1/10 and 1½/40, are discussed.*

*The degree of accuracy of the sphere gap for use in measuring impulse voltages is outlined. The resistance-capacitance and the resistance-cable voltage dividers for the connection of the cathode ray oscillograph are described and their operation analyzed in detail. Both dividers are shown to be satisfactory when properly arranged. Data are given showing that the same kilovolts per millimeter on the oscillogram for widely different wave shapes can be obtained.*

*A specimen table for recording of complete test data is suggested which, it is thought, will tend to eliminate a lack of uniformity and completeness in data previously reported.*

## INTRODUCTION

THIS paper treats of the impulse testing of insulation and with the precautions necessary to produce impulse voltages of the desired wave shape. Such testing involves the construction of circuits of the proper electrical constants, the accurate measurement of these constants, the calculation of electrical variations in the circuit and the checking of these calculations by indicating and recording instruments. Confidence in test results obtained accrues to the extent that this rigorous analysis can be accomplished. This paper presents a summary of some recent experiences directed toward this goal.

## METHOD OF OBTAINING IMPULSE VOLTAGES

As early as 1913 a generator producing high voltage impulses of a predetermined wave shape and voltage was developed in the laboratory and used to determine the time lag and impulse ratio of gaps and insulators, and the impulse strength of insulations.[1] Generators of increasingly higher voltages have since been developed[2,3] and a generator for producing 10,000,000 volts has recently been announced by the High Voltage Engineering Laboratory at Pittsfield.

In present practise the voltages used in impulse testing are obtained by discharging high voltage capacitors. These capacitors are first charged directly from transformers or through vacuum rectifier tubes. For low amplitude impulse voltages the capacitor discharges directly through an arranged discharge circuit, for high voltages several capacitors with interconnected spark gaps are charged in parallel and discharged in series.[3,4,5]

The impulse voltages are obtained by connecting the test piece across the resistance through which the capacitor bank discharges. In Fig. 1 is shown a complete discharge circuit with all constants which influence the shape of the discharge wave. In this circuit the test piece is considered as a capacitance. The constant $C_1$ represents the capacitance of the impulse generator on discharge (all the individual units connected in series). The inductance $L$ includes the natural inductance of the total discharge loop plus any inductance that may be added. The constant $C_2$ represents the capacitance of the connected load or test piece such as sphere gaps, insulators, bushings, etc. The two resistances $R_1$ and $R_2$ are added to the circuit to control the front and length of the wave respectively. With the test specimen $C_2$ connected across $R_2$ the ratio of the crest impulse voltage to the initial capacitor voltage is the voltage efficiency of the lightning generator. This efficiency should be high to permit the attainment of the highest possible impulse voltages with a given capacitor bank.

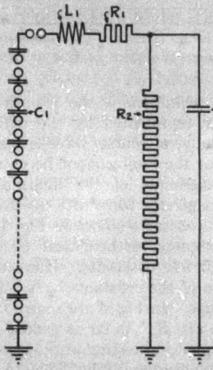

FIG. 1—COMPLETE IMPULSE GENERATOR DISCHARGE CIRCUIT

## METHOD OF OBTAINING SPECIFIED IMPULSE WAVES

Measurement of natural lightning surges[6] in power circuits have shown that the surges which produce damaging effects are of very short time duration (a few microseconds at the most) and practically always unidirectional in polarity. The waves which have been used to greatest extent in the laboratory are unidirectional in polarity (impulses) and have been defined as follows: (½–5), (1–10) and (1½–40). In each case the first figure represents the time-to-crest voltage and the second figure the time-to-half crest on the wave tail in microseconds or millionths of a second, both measured from zero time.

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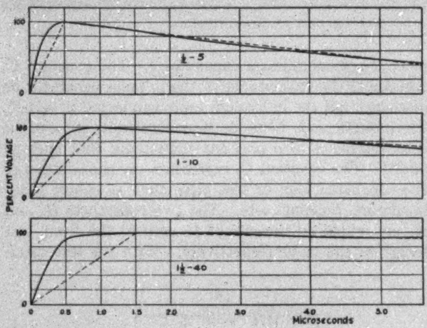


FIG. 2—INPUT VOLTAGE IN USE AT PRESENT

As far as the definitions of the test waves go these three waves are represented by the dotted lines in Fig. 2. Practically, of course, wave shapes with such discontinuities at the crest cannot be obtained. The uninterrupted discharge of the lightning generator capacitor always gives a wave with no discontinuities. The five circuit constants shown in Fig. 1 are always present. A complete mathematical circuit analysis must include all five constants. However, in many instances certain of the constants have little influence on the wave shape. In Fig. 3 are shown two approximate circuits *A* and *B*. As far as general wave shape is concerned in practical testing work either one or the other of these two circuits is relied upon to produce the wave characteristics desired. Both these circuits give wave shapes which are mathematically the difference of two exponentials. As shown elsewhere[4] when the

$$\text{ratio } \frac{T_2}{T_1} = \frac{\text{time to half crest on the tail}}{\text{time to crest}} \text{ is constant}$$

the wave shape is fixed and the same for both circuits *A* and *B*. In Fig. 2 the calculated waves corresponding to the definitions have been plotted in solid lines. It is noted that up to crest value the definitions describe the waves rather poorly. The waves do not rise from zero to crest value at a uniform rate. On the lower part of the wave fronts the kilovolts per microsecond is much greater than it is later when the voltage is approaching the crest value. A large percentage of the total time of the wave front is consumed in rising from 90 per cent to crest. This percentage is greater with the slower waves. This fact causes the chief difference between the three fronts to be near the crest and the three are nearly identical on the first part of the rising front. The waves differ very greatly on the crest and tail. From approximately 0.5 microsecond on, the slow wave has a sustained high voltage within 10 per cent of the actual crest value for 5 or 6 microseconds, compared to 1 microsecond for the fast wave. This fact coupled with the slow voltage decrease to one-half crest value at 40 microseconds as compared to 5 for the fast wave accounts for the low flashover values obtained for the (1½–40) wave. Further, it has been found difficult in several laboratories to produce the 0.5 microsecond to crest with the higher voltage impulse generators and correspondingly longer discharge circuits. The wave obtained requires from 0.5 to 1.0 microsecond to crest. It appears that the different flashover values obtained with the three waves are caused by the flatness of the wave crest and the rate of dropping off of the tail and not by the apparently small differences in wave front.

## METHOD OF MEASURING IMPULSE VOLTAGES

The sphere spark gap[7] and cathode-ray oscillograph[8] are relied upon at present to measure crest voltages and record wave shapes. In tests where the impulse voltage can be repeated the sphere gap when used with proper precautions and corrected for air density can be used to measure crest voltages of impulses within a few per cent. At present the calibration curves which have been adopted include up to 75 cm diameter spheres and voltages up to 1,250 kilovolts crest. There is great need for standardization above this voltage range possibly through 2 meter diameter spheres. As stated above when properly used, the sphere gap is reliable for crest voltage measurements on all the waves being used for practical impulse testing work. That accurate crest voltage measurements on the (½–5) wave are obtained is shown by Fig. 4. This oscillogram was taken with

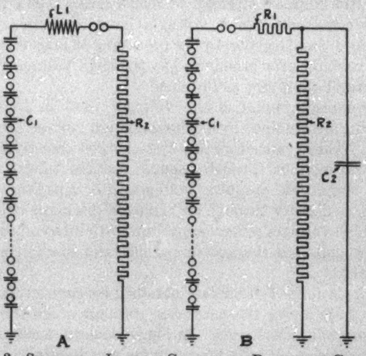


FIG. 3—SIMPLIFIED IMPULSE GENERATOR DISCHARGE CIRCUITS

the crest voltage of the impulse held at the lowest amplitude for flashover. The breakdown, it is noted, is on the crest of the wave and for air breakdown at atmospheric pressure this indicates no time lag.

It happens occasionally that oscillograms are obtained which appear to indicate sphere gap time lag, but such lag can usually be explained in terms of the constants of the sphere gap circuit rather than by the inherent lag in the flashover between the spheres. Various investigators working generally at lower voltages have arrived at a value of $10^{-2}$ microseconds for the inherent time lag of sphere gap breakdown.[9] This order of time lag is not great enough to cause appreciable errors when the crest voltages of the applied waves are being measured. A special problem arises, however, when very high overvoltages with steep front waves are applied to the spheres and the breakdown occurs on the front of the wave. Under these conditions the time lag of the sphere gap is great enough to cause appreciable errors. The magnitude of the error depends upon the per cent overvoltage, the size and spacing of the spheres, and the steepness of the wave front. Such sphere gap characteristics have long been recognized.[1,10]

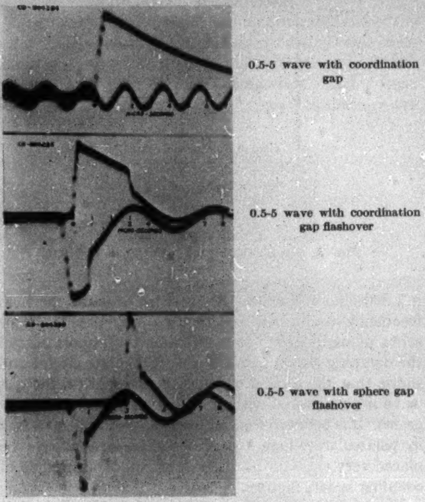


FIG. 4—IMPULSE FLASHOVER OF COORDINATION GAP 0.5–5 WAVE

The cathode-ray oscillograph has been applied to the recording of wave shapes of laboratory lightning with good success. The technique involved is not as yet, however, entirely satisfactory. The problem of time coordination of the oscillograph operation with the impulse generator discharge has been solved with considerable satisfaction in several ways as described elsewhere[4]. The particular remaining problem is that of providing suitable voltage dividers for reducing the impulse voltage to proportions which will permit its application to the cathode-ray oscillograph deflection plates. The ratio of voltage reduction required is of the order of 1,000,000 volts to 1,000, or 1,000 to 1. A proper voltage divider accurately reproduces across the deflector plates of the oscillograph, the impulse wave applied to the test piece, regardless of the shape of the wave used. The ratio of the divider must remain constant regardless of the equivalent frequencies. A divider may reproduce very accurately a smooth wave but tend to dampen out any oscillations that are superimposed on a wave. A thorough study of the characteristics of the divider must, therefore, be made before it can be used with confidence over a wide variety of impulse wave shapes. This is especially essential before using the oscillograph for measuring kilovolts, instead of using the spheres direct.

Two types of voltage dividers have been used to great extent in recent impulse testing work. These types are known as the resistance-capacitance divider and the resistance-cable divider.

The resistance-capacitance divider is shown in Fig. 5. In this divider a capacitance coupling is made near the ground end of the regular discharge resistance, $R_2$, of Fig. 5, to obtain voltage for the deflection plates of the cathode-ray oscillograph. The advantage accruing with this arrangement is that no special tap to the high voltage terminal for the cathode-ray oscillograph is necessary.

The electrical constants of this interconnection between the discharge resistance and the deflection plates must be of such magnitude as will not disturb the true ratio of the discharge resistor as a voltage divider. The portion of the discharge resistor between the tap point and ground has a very low resistance, from 1 to 5 ohms. Currents of a few hundred amperes for the slow waves and several thousand amperes for the fast waves flow through this low resistance. The tap capacitors shown take about two-thirds of the tap voltage, leaving one-third for the deflection plates. The brass tube for elec-

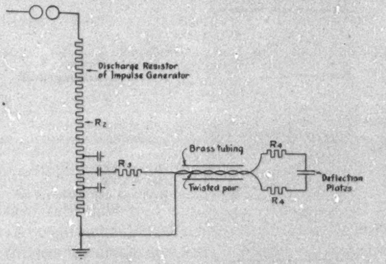
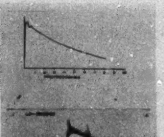


FIG. 5—RESISTANCE-CAPACITANCE VOLTAGE DIVIDER FOR CATHODE RAY OSCILLOGRAPH

trostatic shielding is about 5-ft long and 3-in. in diameter. Capacitance values of this circuit are all of the order of a few micro-microfarads, which capacitance connected across a resistance as low as one to five ohms in the discharge tube preserves a true voltage division. The resistors $R_3$ and $R_4$ are placed in the circuit to dampen its natural oscillation.

Fig. 6 gives a series of oscillograms which show the performance of this type voltage divider particularly with regard to the integrity with which oscillations on the main wave are registered on the oscillogram and the effect of the damping resistors $R_3$ and $R_4$ of Fig. 5. Fig. 6A shows a calculated wave of an approximately (½–5) shape. The capacitance $C_2$ of Fig. 5 in this case consisted of an insulator string and measuring sphere gap in addition to the stray capacitance of the circuit to ground. This capacitance load was sufficient to cause an oscillation of some 8 per cent magnitude superimposed on the fundamental wave shape. Fig. 6B is an oscillogram of this wave shape obtained with zero resistances at $R_3$ and $R_4$. The discharge circuit load oscillation is obscured on this oscillogram by a high frequency oscillation of some 5 million cycles per second. Before taking the oscillogram of Fig. 6C 5,000-ohm resistors were placed at $R_4$. The amplitude of the 5 million-cycle oscillation is greatly reduced. The load oscillation of Fig. 6A is now very clear with about the proper amplitude. The insulator and sphere gap load were removed from the circuit and oscillogram 6D was taken. The load oscillation is not present on this oscillogram and the low amplitude high frequency is still observable. In Fig. 6E a 1,300-ohm resistance was used at $R_3$ and the high frequency oscillation practically disappeared. This series of oscillograms demonstrates the importance of the damping elements in the deflection plate circuit and shows that the oscillations actually present on the test wave are registered with good integrity on the oscillograms. It is believed that for low voltage impulse testing in particular, where the oscillograph can always be placed very close to the discharge circuit this method of coupling is satisfactory.



A—Calculated wave insulator string and sphere-gap load on discharge circuit

B—$R_3 = 0$
$R_4 = 0$

C—$R_3 = 0$
$R_4 = 5{,}000$
Insulator string and sphere-gap load on discharge circuit

D—$R_3 = 0$
$R_4 = 5{,}000$ ohms
No load on discharge circuit

E—$R_3 = 1{,}300$
$R_4 = 5{,}000$
With rod gap flashover on positive wave

Fig. 6—Performance of Resistance-Capacitance Divider

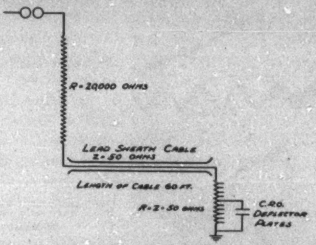
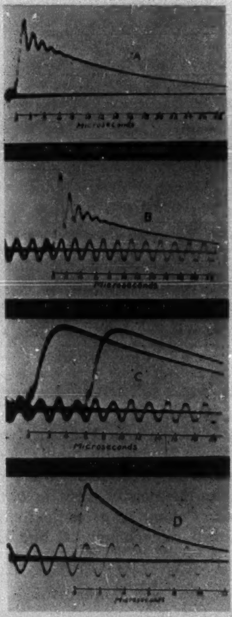


Fig. 7—Resistance-Cable Voltage Divider

The arrangement of the resistance-cable divider is shown in Fig. 7. It consists of 20,000 ohms of resistance at the impulse generator end, and 50 ohms at the oscillograph end of a lead sheath cable. Both of these resistances are made up of resistance wire non-inductively wound on flat cards. The cable is 60-ft long and acts as a shielded lead from the lightning generator to the oscillograph. The 50 ohms to ground at the oscillograph end of the cable is equal to the surge impedance of the cable. As this resistance is decreased below the surge impedance of the cable reflections occur in the cable which tend to increase the magnitude of any superimposed oscillations and also to decrease the time to reach crest. As this resistance is increased above the surge impedance of the cable the superimposed oscillations are rapidly damped out and the time to reach crest is increased very appreciably. It is very necessary therefore to determine carefully by impulse methods the surge impedance of the cable. If this is not done and the desired value of impedance is not carefully maintained the calibration of the oscillograph deflection will not be the same on the (½–5) and the (1½–40) waves. In Fig. 8A and Fig. 8B can be seen the effect on the magnitude of a superimposed oscillation when the resistance at the oscillograph end of the lead sheath cable is varied. By varying this resistance and holding the same voltage across the test piece, as measured by spheres, with both the smooth wave (Fig. 8c) and the highly oscillatory waves, a value of resistance may be found which gives the same deflection for both waves. When this value of resistance is used the wave shapes recorded check with wave shapes obtained with other types of dividers and also with the calculated wave shapes. Fig. 8D shows a (½–5) wave as taken with the resistance-cable divider.

The 20,000 ohms at the lightning generator end of the cable was chosen to give the desired ratio. If this resistance is increased to a value much in excess of 20,000 ohms a sloping off or lengthening of the faster front waves and a damping of superimposed oscillations are detected. With the (½–5) and (1½–40) waves, no change in the wave shape can be noticed when the resistance is decreased below 20,000 ohms. This resistance is decreased below 20,000 ohms to reduce the ratio of the divider when desired.



D—0-5/5 wave as obtained with resistance-cable divider

FIG. 8—PERFORMANCE OF RESISTANCE-CABLE DIVIDER

A somewhat special problem is involved when high overvoltages are being applied to the test piece, with the steepest front waves obtainable, and it is desired to measure the sparkover voltage with the oscillograph. It is necessary to decrease the divider resistance to far below 20,000 ohms in order that the ratio of the divider does not change. This is due to the extremely high rate of rise of voltage at the time of sparkover on the front of the wave.

Inductance in the divider will cause certain errors at exceedingly steep fronts. All precautions should be taken to secure a non-inductive resistance. If it is found impractical to secure a sufficiently non-inductive metallic resistor, a water tube resistor may be substituted. Another source of error in the divider is the presence of capacitance to ground.

The presence of the cable will introduce an error if it is grounded through a resistance whose value is not equal to the surge impedance of the cable. The losses in the cable may also introduce an error where they are appreciable. However, these errors can be readily predetermined and in our work when they are appreciable, they are taken into consideration. For experiments with circuits in which the resistances of the resistance-cable divider introduces appreciable error, a specially designed capacitance divider is used.

In addition to a demonstration of integrity of registration of wave shape on the oscillograph it is also necessary to show that the oscillograph deflection can be interpreted in terms of kilovolts. It has been the usual practise to refer the oscillograph deflection to sphere gap measurements of voltage across the test specimen. To assure confidence in test results this calibration must be taken as previously described on a fast and on a slow wave. With the same voltage divider and oscillograph connections the kilovolts per millimeter deflection on the (½–5) wave must check that obtained on the (1½–40). This check has been obtained with both the resistance-capacitance type of divider and the resistance-cable divider.

A specimen of data obtained during such an oscillograph calibration is shown in Table I.

TABLE I—VOLTAGE CALIBRATION OF CATHODE-RAY OSCILLOGRAPH

| Wave shape | Type of voltage divider | Impulse voltage kilovolts (corrected) | Oscillograph deflection | |
|---|---|---|---|---|
| | | | Millimeters | Kv/mm |
| ½-5 | Resistance-capacitance | 500 | 47.5 | 10.53 |
| 1½-40 | Resistance-capacitance | 500 | 48.5 | 10.31 |
| ½-5 | Resistance-cable | 593 | 38.6 | 15.35 |
| 1½-40 | Resistance-cable | 594 | 38.7 | 15.35 |

These data show that with properly constructed circuits a consistent calibration may be obtained for different waves and voltage dividers. The necessity of making such tests and obtaining results which check are obvious.

There are, of course, many factors concerned with the arrangement of parts and technique of operation of the generator, test specimen, sphere spark gap, voltage divider and cathode-ray oscillograph which make for incorrect data when they are not carefully considered. At present, space will not permit their consideration. At this time a most important problem is that of tabulation and presentation of data.

## TABULATION AND PRESENTATION OF DATA

No satisfaction will be obtained throughout the field of impulse testing until the various laboratories are able to check results obtained in other laboratories. The most frequent stumbling block encountered in the achievement of this end has been that of inadequate recording and exchange of data. In an effort to improve this situation the authors of this paper wish to present a specimen tabulation, Table II, which they believe will assist greatly if adhered to. The specimen given is taken from a test on square rod coordination gaps.

TABLE II—MINIMUM WAVE FLASHOVER OF COORDINATION GAPS ON POSITIVE POLARITY (½–5) WAVE

| Circuit calibration data | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coordination gap | | Measuring sphere gap | | | | | | | | | Cathode-ray oscillograph | |
| Circuit rating kv | Gap spacing in. | Sphere diameter cm | Gap setting cm | Cal. curve voltage kv | Impulse generator excit. voltage volts | Dry temp. °C | Atmos. pressure cm Hg | Relative air density | Sphere gap correction factor | True voltage kv | Deflection total mm | Deflection sensitivity kv/mm |
| 69 | 18.75 | 50 | 16.4 | 400 | 46 | 14 | 74.83 | 1.021 | 1.02 | 408 | 26 | 15.7 |
| Column numbers | | | | | | | | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |

| Gap test data | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cathode-ray oscillograph | | | | | Coordination gap corrections for standard conditions | | | | | | | |
| Deflection tap No. | Oscillogram No. | Impulse generator primary volts | Oscillogram deflection at crest mm | Voltage from oscillogram kv | Temp. wet bulb °C | Relative humidity % | Content saturated air at dry temperature gr/cu ft | Content saturated air at relative humidity gr/cu ft | Humidity correction | Total correction humidity and air density | Corrected flashover voltage kv | Date of test |
| 2 | 903740 | 52 | 29.5 | 464 | 7.5 | 35 | 5.227 | 1.83 | 1.058 | 1.037 | 482 | 3–9–32 |
| Column numbers | | | | | | | | | | | | |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |

It is granted of course that other forms of data presentation may be better adapted to other tests. The principal point is that the data should be as complete as shown in this table. The column headings are in most cases self-explanatory and the testing procedure is somewhat apparent from the table headings and entries. Outlining briefly, the columns, 1 and 2 describe the test piece, column 3 gives the diameter of the calibrating spheres, column 4 the gap spacing of the spheres, column 5 the standard flashover at 25 deg C, 76 cm pressure for this gap spacing. Column 6 gives the impulse generator excitation voltage for the gap flashover as described in columns 3, 4 and 5 but under prevailing test conditions rather than standard conditions. The voltage flashover of the gap must be determined by correcting column 5 to test conditions. Columns 7 and 8 give temperature and pressure readings for making this correction and columns 9 and 10 give the correction factors taken from the accepted tables.[11] Column 11 gives the true voltage obtained at sphere gap flashover. A cathode-ray oscillogram was obtained at this flashover voltage with the gap sparking at the crest of the wave. The maximum deflection of the oscillogram is entered in column 12, and column 11 divided by column 12 gives the oscillograph sensitivity. A similar procedure performed with the test piece substituted for the sphere gap obtains flashover values desired. Column 14 gives the deflection tap number as shown in Figs. 5 and 7 and column 15 the oscillogram number. Column 16 gives the impulse generator excitation voltage for the rod gap flashover and column 17 the oscillograph deflection. The flashover voltage under test conditions is given in column 18. This value must be corrected to standard conditions of temperature, pressure, and humidity. Column 19 gives the temperature of the wet bulb. Column 20 the relative humidity from columns 7 and 19 and a standard humidity chart. Column 21 gives the table value of moisture content of saturated air at temperature of column 7. Column 22 gives the moisture content of the air under test conditions. Column 23 gives the humidity correction as obtained from column 22 and the following tabulation:

HUMIDITY CORRECTION

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Add | 1.25% | for | (½–5) | wave for each | 1 grain/cu ft | below | 6.5 grains/cu ft |
| " | 1.50% | " | (1 –10) | " " | " 1 " | " | 6.5 " |
| " | 2.33% | " | (1½–40) | " " | " 1 " | " | 6.5 " |

The above correction is subtracted for test values of humidity above 6.5 grains per cu ft.

Column 24 gives the correction factor obtained by combining columns 23 and 9. Column 25 gives the final corrected flashover value at 25 deg C temperature 76 cm of mercury pressure and 6.5 grains per cu ft humidity. Column 26 gives the date of test.

Although vapor pressure in inches of mercury is mentioned in the A.I.E.E. Standards[12] as the unit of absolute humidity, it has become more common to express absolute humidity in terms of grains per cu ft.

Present knowledge of variation of flashover with humidity does not indicate that either reference standard has more significance than the other. Either may be used by obtaining dry and wet thermometer readings and referring to existing tables. The accumulation of laboratory data on flashover and its study with reference to moisture weight and vapor pressure should permit the relative significance of each to be determined.

A tabulation and presentation of data in arrangement and completeness at least as thorough as that given in Table II are necessary if satisfactory checks are to be obtained in several laboratories.

### CONCLUSIONS

In concluding the authors desire to point out again the necessity of careful attention to discharge circuit arrangements, measurement of circuit constants, calculation of discharge wave shapes and cathode-ray oscillograph checks. Great progress awaits the general adoption of this point of view.

Sparkover voltage differences with the (½–5), (1–10) and the (1½–40) waves are believed to be more the result of differences in the wavelength than in the wave front. By definition the waves differ by 8 to 1 in duration and only 3 to 1 in front. Moreover, the waves do not rise uniformly to their crest values, but rise rapidly at first and a large proportion of the total length of the front particularly for the longer fronts is consumed in approaching the crest. The difference in the fronts is, therefore, even less than 3 to 1.

The resistance-capacitance and the resistance-cable voltage dividers are shown to be satisfactory when properly arranged. A carefully adjusted value of cable impedance is required for the resistance-cable divider. It is shown that on a fast or slow wave the calibration of the cathode-ray oscillograph deflection in kilovolts per millimeter can be obtained and will check with either type of voltage divider.

The authors have recognized that an important cause of the disagreements between laboratories is the lack of uniformity and completeness in reporting results of impulse tests. A specimen table form which it is believed will at least suggest the lines along which reports should be made has been presented.

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## Discussion

For discussion of this paper see page 553.

# The Measurement of High-Surge Voltages

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***Synopsis.***—*With the application of surge tests to high voltage electrical apparatus, the question of the measurement of high-surge voltages has become a subject of prime importance. It is accordingly desired in Part I to show the practical work done in the laboratory at Sharon to calibrate the measuring devices, and in Part II to study the more interesting fundamental relationships that affect the operation and accuracy of these measuring devices.*

*The methods of voltage measurement used are the resistance potentiometer, capacity potentiometer, and sphere gap. The potentiometers serve as dividers of the high-surge voltages for measurement at the cathode-ray oscillograph. The resistance potentiometer is a fundamental standard but requires consideration of its limitations for very rapid phenomena. In cases where these can be compensated for or are negligible, the resistance potentiometer method is very desirable. The capacity potentiometer is a secondary standard which can be calibrated. If corona and oscillations can be eliminated, it is a very desirable method of measurement, inasmuch as it is less subject to distorting the wave shape of the surge. The sphere gap is useful as a secondary standard for occasional check measurements, and it is of interest that formulas derived from smaller gaps still hold, as indicated by the check between the calculated curve for the 200-cm sphere gap and the calibration points with the resistance potentiometer.*

* * * * *

## Part I—Laboratory Technique on Measurement of High-Surge Voltages

### METHODS OF MEASUREMENT

THE measurements at the Sharon High-Voltage Laboratory are made by means of a cathode-ray oscillograph, using either a resistance or a capacity potentiometer. A sphere gap also is used to check the readings in some cases, and as a secondary or calibrated standard.

### DESCRIPTION AND CALIBRATION OF THE CATHODE-RAY OSCILLOGRAPH

The type of cathode-ray oscillograph used has been described previously.[1] A complete knowledge of the theory of the oscillograph is not essential, but an understanding of its calibration and the sources of error is necessary in practical operation. For this reason, a brief description of the oscillograph is given, and the essential parts are shown in Fig. 1. It consists primarily of a glass tube, at one end of which the cathode is placed. At the other end of the tube, a perforated plate forming the anode filters the cathode-ray beam, which then passes between deflection plates in the main body of the oscillograph. It can be shown that any electrostatic deflection of the cathode-ray beam is inversely proportional to the cathode voltage, and directly proportional to the field intensity between the plates.[1,2] Therefore, it is essential in using the oscillograph to see that a constant cathode voltage is maintained and as the field intensity between the deflection plates depends on the voltage across the plates and their separation, and if the separation can be varied, care must be taken to keep the setting correct for any calibration. Except for the principle of operation, the cathode-ray oscillograph then does not differ in application from other types of measuring devices. It can be given an individual calibration and used with suitable voltage dividers exactly as in the case of the more common type of oscillograph.

In order to determine the calibration of the oscillograph alone, the arrangement of test shown in Fig. 1 was made. Both negative and positive continuous voltages of different amplitudes were impressed on the voltage plates. These voltages were measured by a calibrated static voltmeter, and the corresponding deflections of the cathode-ray beam measured on oscillograms. These were scaled and the results tabulated, to determine the volts per inch deflection for various voltages and plate settings. The results of these tests showed that the deflections were proportional to the

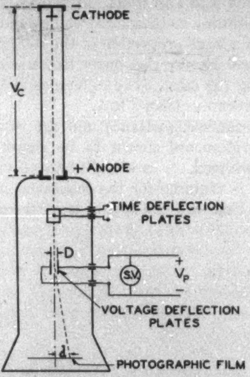

FIG. 1—SCHEMATIC DIAGRAM OF LABORATORY SET-UP FOR VOLTAGE CALIBRATION OF CATHODE-RAY OSCILLOGRAPH

$V_C$, cathode voltage
$V_P$, voltage on deflection plates measured with static voltmeter (*S.V.*)
*D*, separation of voltage deflection plates
*d*, deflection on photographic film

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*Westinghouse Electric & Mfg. Company, Sharon, Pa.

1. For references, see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N.Y., January 23-27, 1933.*

voltage, and for the plate setting used in calibrating the resistance potentiometer, that 903 volts per inch deflection was obtained, over a test range from 819 to 1,570 volts. A sample oscillogram taken during this calibration is shown in Fig. 2A.

### THE RESISTANCE POTENTIOMETER

The oscillograph cannot be used directly at voltages of 1,000,000 and over used in the laboratory, but some type of voltage divider is necessary to obtain voltages of approximately 1,000 volts for measurement at the cathode-ray oscillograph plates. Further, this must be done in strict proportionality during any interval of time. One of the simplest means is the use of the resistance potentiometer, which is shown diagrammatically in Fig. 3. It consists of two resistances, generally connected by a cable.[12] It can readily be seen that if the voltage is continuous, the potentiometer differs in no way from that commonly used for voltmeter standardization and calibration. If very rapid transients exist and if the resistances have no distributed capacity and no self-inductance, the voltages still will divide proportionately, but it is necessary in order to avoid reflections at the oscillograph end of the cable lead, to have the surge impedance of the cable exactly equal to the resistance at the oscillograph. This is shown in Fig. 2, oscillograms *B*, *C* and *D*. However, if such potentiometers do have distributed capacity, they will not divide the voltage proportionally at all instants, as shown in Part II, and also as indicated by measurements.

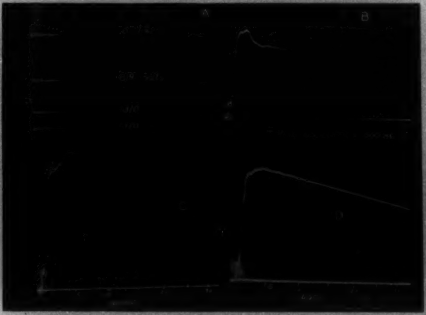

FIG. 2

*A*. Oscillogram on calibration of voltage deflection plates of cathode ray oscillograph

*B-C-D*. Oscillograms showing effect of resistance at terminal-end of cable on surge voltage at cathode ray oscillograph

- *B*. "Low resistance" terminal loading
- *C*. "High resistance" terminal loading
- *D*. "Correct resistance" terminal loading, *i. e.*, terminal resistance equal to effective surge impedance of cable

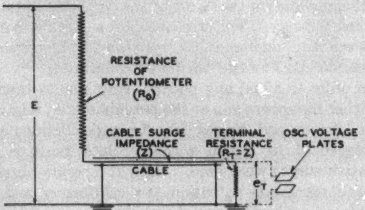
RESISTANCE OF POTENTIOMETER ($R_0$)
E
CABLE SURGE IMPEDANCE (Z)
CABLE
TERMINAL RESISTANCE ($R_T$=Z)
OSC. VOLTAGE PLATES
$e_T$

FIG. 3—PLAIN RESISTANCE POTENTIOMETER CONNECTED TO CABLE

Terminal-end of cable loaded with proper resistance and connected to voltage deflection plates of cathode-ray oscillograph

In addition to the errors caused by the distributed capacity in the resistance potentiometer, it was found that some errors existed due to effects in the cable. It is therefore desirable to use cable with low distortion and loss effects, and, if possible, of short length. Illustrative of this, oscillograms *B* and *A* in Fig. 4, show the effects in 50 feet of cable against those in 500 feet of cable for similar surges. With the type of cable used at Sharon, to make this error as small as possible, only 42 feet of cable is used.

FIG. 4—OSCILLOGRAMS SHOWING EFFECT OF LENGTH OF CABLE ON SURGE VOLTAGE AT OSCILLOGRAPH AND COMPARISON BETWEEN RESISTANCE AND CAPACITY POTENTIOMETERS

- *A*. Measurement with 500-ft cable (resistance potentiometer)
- *B*. Measurement with 50-ft cable (resistance potentiometer)
- *C*. Measurement with capacity potentiometer
- *D*. Oscillogram of 200-cm sphere gap flashover. This oscillogram shows the desirability of using a long, flat wave for the calibration of the sphere gap (resistance potentiometer measurement)

The resistance potentiometer is not suitable for measurements in which the rate of change is more rapid than that to which the potentiometer circuit can respond. It does, however, have the great advantage of being a means of exact quantitative measurement for phenomena not too fast for its response. The resistance potentiometer at Sharon consists of non-inductive, wire wound, oil immersed resistors having a total resistance of 34,000 ohms. The cable lead has a calculated surge impedance of approximately 44.4 ohms. The resistance at the oscillograph is 43.5 ohms, which is close enough to the true cable surge impedance to cause no apparent trouble due to reflection. Since the calibration of the oscillograph was 903 volts per inch, the calibration of the combined oscillograph and resistance potentiometer is $903 \times \frac{34{,}044}{43.5}$ or 707,000 volts per inch deflection.

## SPHERE GAP CALIBRATION

The sphere gap has been used for some time as a standard of voltage measurement. It is, however, a secondary standard, depending upon fundamental calibration made originally by measurements of capacity and current.[3] From studies of sphere gaps, it has been found that their calibration can be represented by formulas which differ slightly in the work of different observers.[4] It was then possible to calculate the calibration of the sphere gap, and this was done. This work was desirable, since the gap at Sharon uses 200-cm spheres, for which no calibration had previously been made. The calculation for the 200-cm sphere gap was made by using the 25-cm sphere gap calibration* and increasing the voltage and spacing scales proportionately to the sphere diameters, and further correcting for the sparking gradient for the two spheres by the proportionality relationship: $\left(1 + \frac{0.52}{\sqrt{a}}\right)$, where $a$ is the radius of the spheres in cm. It was thought possible that the extrapolated sphere gap calibration might not be correct; also that the calibration at low frequency might not be accurate for surge voltages, since the laws of the gap as established by the formula might be changed due to the effect of the surges and also due to their polarity.[5] For these reasons, a check was made between a fundamental calibration with the resistance potentiometer and the calculated calibration.

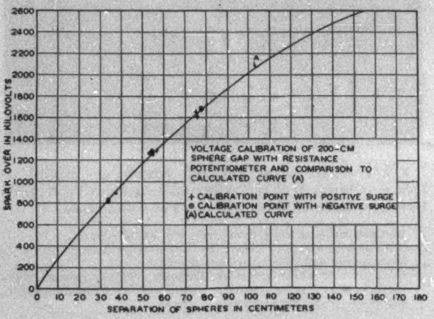

FIG. 5—VOLTAGE CALIBRATION OF 200-CM SPHERE GAP WITH RESISTANCE POTENTIOMETER AND COMPARISON TO CALCULATED CURVE

(Relative air density = 1.00)

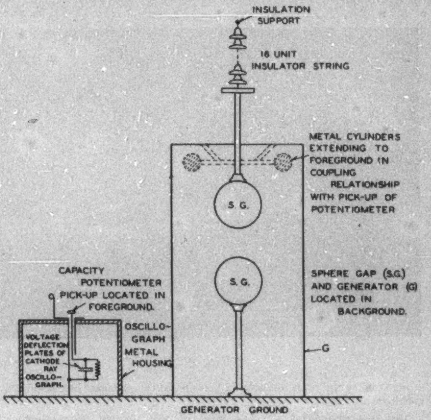
INSULATION SUPPORT
16 UNIT INSULATOR STRING
METAL CYLINDERS EXTENDING TO FOREGROUND IN COUPLING RELATIONSHIP WITH PICK-UP OF POTENTIOMETER
S. G.
S. G.
SPHERE GAP (S.G.) AND GENERATOR (G) LOCATED IN BACKGROUND.
CAPACITY POTENTIOMETER PICK-UP LOCATED IN FOREGROUND.
OSCILLO-GRAPH METAL HOUSING
VOLTAGE DEFLECTION PLATES OF CATHODE RAY OSCILLO-GRAPH.
G
GENERATOR GROUND

FIG. 6.—VERTICAL CROSS-SECTION OF LABORATORY SHOWING METAL CYLINDERS OR STATIC SHIELDS OF LARGE RADIUS TO ELIMINATE CORONA IN SPACE ADJACENT TO PICK-UP OF CAPACITY POTENTIOMETER

In order to avoid any possible error due to time lag in either the sphere gap or the potentiometer, relatively long, flat-topped waves free from oscillations were employed (1 to 1½-40 waves). Both positive and negative surges were used. Both the points obtained by the resistance potentiometer calibration and the calculated calibration are shown in Fig. 5. A sample calibration point is shown on the oscillogram *D*, Fig. 4. The voltage by sphere gap flashover and the calculated sphere gap calibration indicated 902,000 volts. The deflection of the oscillogram is 1.26 inches, corresponding to 707,000 by 1.26, or 891,000 volts, which checks within 1 per cent. Another sample calibration point shown on oscillogram *B*, Fig. 12, checks within a small fraction of 1 per cent.

This work indicates that the potentiometer and oscillograph readings check the sphere gap indications for waves of duration not too short, and also that this is independent of polarity. Variations from this are found when the phenomena are very fast and the resistance potentiometer cannot respond, or the sphere gap shows time-lag characteristics.

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*Similar calculations of the 200-cm sphere gap from the present A.I.E.E., 12.5-cm, 50-cm and 75-cm sphere gap calibrations were made, with resultant small percentage variations from the calculated curve here shown. The 25-cm sphere gap calibration was used, as this gap was the one originally calibrated by fundamental measurement.

## THE CAPACITY POTENTIOMETER

The capacity potentiometer, as its name implies, depends on the oscillograph measuring the voltage across a component of capacity. The voltage is here divided inversely as the capacity components. It has certain advantages; for example, it eliminates almost all error due to time delay in response, which is present in the resistance potentiometer, but it is difficult to eliminate inherent oscillations, and care must be taken to keep the capacity relations unchanged. It is used in Sharon, because, due to arrangement of the laboratory, these difficulties could be practically overcome; full advantage of its rapid response could be taken; and because of its desirability where transformer power follow tests were being made, to avoid power currents causing damage to the potentiometer.

FIG. 7—SURGE GENERATOR, 200-CM SPHERE GAP AND SHIELDS

The arrangement of the parts at Sharon is shown in Fig. 6 and is illustrated in Figs. 7 and 8. Other arrangements have been used where the capacities were self-contained, but for lower voltages,[11] and similar arrangements have been and are used in surge distribution tests on transformer windings, where no great difficulty is experienced if all leads are carefully shielded. For high voltage, it is more difficult to provide a separate self-contained potentiometer, and a pick-up as shown in Fig. 6 is used to provide the necessary coupling.

The calibration of the capacity potentiometer was made by taking oscillograms of similar waves by the use of both resistance and capacity potentiometers. The calibration was made using a relatively long, flat-topped wave, as in the case of the sphere gap calibration. The results obtained are shown on Fig. 9.

This calibration is quite interesting, inasmuch as it indicates a linear calibration in volts per inch for the negative waves, but that the deflection increased more than proportionately for the higher positive waves. Also, it was found that on flashover, the negative wave always came to the zero line, whereas the positive waves did not indicate a complete collapse to zero. These phenomena are shown on the oscillograms, Fig. 10. A previous calibration of the potentiometer, when no special provisions were made to eliminate corona, is shown in Fig. 11. In this case, the variation from linear calibration seemed excessive and an effort was made to improve the situation. It is of interest to note that this calibration was made over a period of three months, and does indicate the constancy of the calibration. The discrepancy between positive and negative waves was also found in measurements similarly made in Trafford. It was early believed that the phenomena were due to space charge and in turn due to corona. It was accordingly decided to install metallic cylinders or shields of large radius, with a view to eliminating

FIG. 8—PICK-UP ELEMENT OF CAPACITY POTENTIOMETER

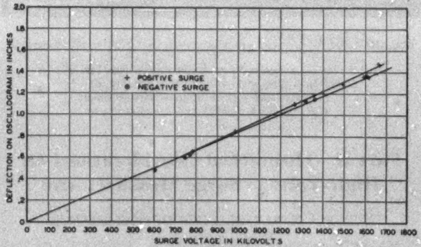

FIG. 9—CALIBRATION OF CAPACITY POTENTIOMETER OBTAINED AFTER INSTALLATION OF STATIC SHIELDS OF LARGE RADIUS; STATIC SHIELDS LOCATED AS SHOWN IN FIG. 6

this space charge in the immediate vicinity in coupling relationship with the pick-up element. How successful this was is shown by a comparison of the calibration curves in Figs. 9 and 11. The arrangement of the shields is shown dotted in Fig. 6. An explanation of the effect of space charge within the scope of this paper is given in Part II.

The successful development of the capacity potentiometer was of advantage because it permitted more accurate reproduction of extremely short surges. A sample comparison of identical surges using the resistance and capacity potentiometers is shown in oscillograms *A*, *B* and *C* of Fig. 4, and in oscillograms *A* and *B* (Fig. 12) at the flashover of the sphere gap. Its other advantage is its freedom from damage due to transformer testing with dynamic power connected.

FIG. 10—OSCILLOGRAMS OF POSITIVE AND NEGATIVE SURGES

*A* and *B*. Taken with no static shields (see Fig. 6)
*C* and *D*. Taken with static shields (see Fig. 6)
*R P*. Resistance potentiometer measurement
*C.P.* Capacity potentiometer measurement

## Part II—Theoretical Considerations on High-Voltage Surge Measurement

### SURGE CHARACTERISTICS OF RESISTANCE POTENTIOMETER

The circuit in Fig. 3 represents correctly the equivalent circuit of the resistance potentiometer provided the maximum rate of application of the surge voltage *E* with respect to time does not exceed a given limit. It is the purpose here to analyze the maximum surge voltage variation that can be recorded accurately with resistance potentiometers.

The general circuit diagram of the resistance potentiometer is given in Fig. 13. A non-inductive resistance is shown, as the inductance is small and is of secondary importance in the practical problem at hand. A uniformly distributed resistance-capacity network will first be considered, where:

$N$ = total number of resistance elements
$R$ = resistance of each element
$C_1$ = capacity of each element to ground
$C_2$ = capacity across each element
$C_g = NC_1$; $C_e = C_2/N$; $R_o = NR$
$E$ = rectangular surge voltage applied at time $t = 0$
$n$ = number of resistance elements from ground end
$e$ = voltage across then $n$ elements
$p$ = Heaviside's operator $d/dt$

The response of this network is expressed operationally[6] as

$$e = \frac{\sinh \sqrt{\dfrac{RC_1 p}{1 + RC_2 p}}\, n}{\sinh \sqrt{\dfrac{RC_1 p}{1 + RC_2 p}}\, N} E = \frac{E}{F(p)}$$

From the Heaviside expansion theorem, the roots may be found by equating $F(\lambda)$ to zero, which gives

$$\sinh \sqrt{\frac{RC_1 \lambda}{1 + RC_2 \lambda}}\, N = \sinh jk\pi =$$

and $\lambda = -\dfrac{k^2 \pi^2}{R_o (C_g + k^2 \pi^2 C_e)}$, where $k = 1, 2, 3 \ldots$

The steady-state voltage is given as the

$$\lim_{\lambda \to 0} \frac{E}{F(\lambda)} = \frac{n}{N} E$$

and the coefficients of the transient terms are derived from

$$\lambda \frac{d}{d\lambda} F(\lambda) = \frac{\cosh \sqrt{\dfrac{RC_1 \lambda}{1 + RC^2 \lambda}}\, N}{2 \sinh \sqrt{\dfrac{RC_1 \lambda}{1 + RC_2 \lambda}}\, n} \times \frac{\sqrt{\dfrac{RC_1 \lambda}{1 + RC_2 \lambda}}\, N}{(1 + RC_2 \lambda)}$$

Then, from

$$\cosh jk\pi = \cos k\pi \text{ and } \sinh jk\pi \frac{n}{N} = j \sin k\pi \frac{n}{N}$$

and the above expressions, substitution in the expansion theorem gives the final solution:

$$e = \frac{n}{N} E + \frac{E}{\pi} \sum_{k=1}^{k=\infty} \frac{2 \sin\left(k\pi \dfrac{n}{N}\right)}{k \cos(k\pi)} \frac{\epsilon^{-\frac{k^2 \pi^2 t}{Ro (C_g + k^2 \pi^2 C_e)}}}{\left(1 + k^2 \pi^2 \dfrac{C_e}{C_g}\right)} \quad (1)$$

Representative values of the circuit constants $R_e$, $C_g$ and $C_c$ inserted in equation (1) give the voltage-time curves of Fig. 14. These characteristic curves show that if potentiometers are to respond rapidly to abrupt surge voltages, they must have relatively low resistance and small ground capacity. This is also shown in Fig. 15 (*A* and *B*), where calculated curves of response are compared with two typical fast surges. Such discrepancies, as indicated, between fast surges to be measured and the recorded oscillograms have been observed in the laboratory when resistance potentiometers have been used.

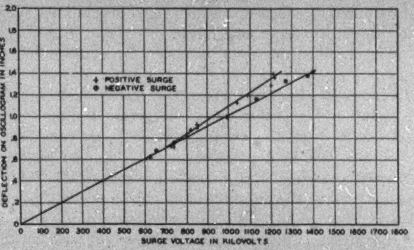

Fig. 11—Calibration of Capacity Potentiometer Without Static Shields (Experimental Results Taken Over a Period of Three Months)

Laboratory arrangement without static shields (see Fig. 6)

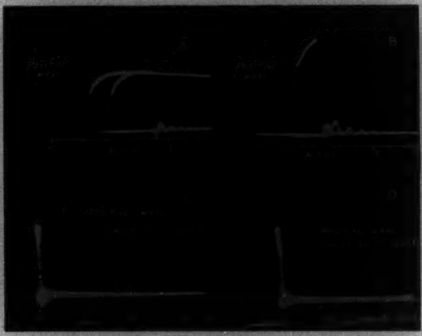

Fig. 12

*A* and *B*. Further comparison of oscillograms using resistance and capacity potentiometers

*A*. Capacity potentiometer measurement, one of the oscillograms showing flashover of 200-cm sphere gap

*B*. Resistance potentiometer measurement showing flashover of 200-cm sphere gap

*C* and *D*. Flashover of positive surges showing the subsistence of the positive space charge for hundreds of microseconds after the collapse of the surge voltage

In practise, the undesirable effect of ground capacity can be materially reduced by locating the potentiometer in a uniform electrostatic field. In the laboratory this can be accomplished by locating the potentiometer resistance in close proximity to the surge generator and extending uniformly to its full height, inasmuch as the voltage distribution from earth to the high potential terminal of the surge generator is practically uniform. It should also be observed that the resistance potentiometer should be connected to the sphere gap through as short a conductor as is physically possible. This method has been used successfully at the Sharon Laboratory, and a degree of response even closer than illustrated in curve *A* of Fig. 14 has been obtained. This is shown by comparing oscillogram *B* in Fig. 12, illustrating a sphere gap flashover measured by the resistance potentiometer, with oscillogram *A*, which shows a similar flashover measured with the capacity potentiometer. It will be noted that oscillogram *A* shows the voltage collapsing immediately upon flashover, whereas in oscillogram *B* the collapse of voltage would appear to require approximately one quarter of a microsecond. Even this is unusually good response for resistance potentiometer. In fact resistance potentiometers as used at Trafford and Sharon are entirely satisfactory for time-lag curve determinations.

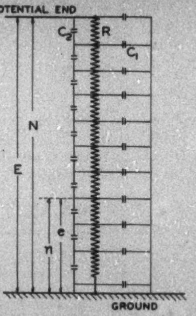

Fig. 13—Circuit of Resistance Potentiometer

(Resistance-capacity network)

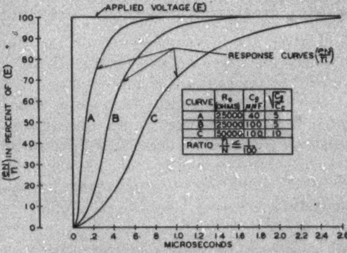

Fig. 14—Response of Resistance-Capacity Network to Rectangular Surge

As shown in Fig. 3, the high resistance component of the resistance potentiometer connects at its low-voltage end through a cable terminated by a resistance. The voltage plates of the cathode-ray oscillograph connect across the terminal resistance. It was stated in Part I that the terminal resistance must be closely adjusted to a value equal to that of the effective surge impedance of the cable, otherwise reflections are superimposed on the surge measured. The ratio of the voltages $e_T'$ and $e_T$, which correspond respectively to reflection and to no reflection at the terminal-end resistance, is readily derived and is given by the expression:

$$\frac{e_T'}{e_T} = \frac{2Z}{R_T + Z} \tag{2}$$

Referring to Table I, the experimental results may be compared to calculated values:

TABLE I

| Film | $R_T$ | $e_T'/e_T$ | |
|---|---|---|---|
| (Fig. 2) | (Ohms) | Calculated | Exper. |
| *B* | 32 | 1.17 | 1.16 |
| *C* | 56 | .88 | .88 |
| *D* | 44 | 1.00 | 1.00 |

Comments: $Z = 44$ (experimental) and $R_o = 34{,}000$ ohms.
$Z = 44$ approx. (calculated).
Length of cable 500 ft.
Time of propagation in 500 ft of cable approximately 1 μsec.

As indicated in equation (2) and Table I, it is essential that $R_T = Z$ for complete elimination of reflections. With a short length of cable of proper characteristics, distortion and attenuation even of steep fronted surges may be reduced to a negligible amount.

## SURGE CHARACTERISTICS OF CAPACITY POTENTIOMETER

Fig. 6 gives the physical set-up of the capacity potentiometer as used at the Sharon High-Voltage Laboratory for the purpose of surge voltage measurement. It is very desirable that the pick-up element of the potentiometer be located in an electrostatic field such that its potential be invariably directly proportional to the surge generator voltage measured irrespective of the amplitude of surge voltage, the polarity of surge voltage, or other effects due to ground.

The theory of the effect of the amplitude and polarity of surge voltages on the operation of the capacity potentiometer is simply and best explained in Fig. 16. Referring to Fig. 16A, where both $h$ and $r$ are here considerably smaller than $d$, the potential at point $p$ is for practical purposes simply expressed as:[7]

$$v_p = \frac{\dfrac{2h}{d} V}{\log \epsilon \dfrac{2d}{r}} = \alpha V \tag{3}$$

The factor $\alpha$ may be termed the reduction ratio of the capacity potentiometer. As shown in Fig. 16C, this coefficient remains constant provided the equal and opposite electric charges remain confined exclusively to the equipotential surfaces of the electrodes. In case the voltage $V$ exceeds a critical value $V_o$, overstress at the surface of the conductor occurs and electrical breakdown of the air adjacent to the conductor takes place.[8] The electrical charge then becomes partly confined to the surface of the conductor and partly distributed as a space charge in the ionized air adjacent to the conductor, increasing the effective radius.

Fig. 17 illustrates the electrical breakdown in the highly stressed region in the air adjacent to the conductor electrode. It is necessary to distinguish between positive and negative surge voltages. Voltages that exceed the disruptive critical voltage $V_o$ are considered.

In the case of a positive surge $V$ applied between conductor and ground, a positive electrostatic field is established in the dielectric, and thus a positive potential is recorded at $p$. Up to the potential $V_o$, for which the gradient at the conductor does not break down the air adjacent, the voltage $v_p$ bears a linear relationship to the surge voltage $V$. As the potential $V$ exceeds the disruptive critical voltage $V_o$, the gradient at the conductor exceeds the ionizing gradient and thus electrical breakdown of the air takes place. As the result of ionization of the air at the conductor, positive ions and electrons are generated. Under the action of the resultant electrostatic field, the electrons move to the conductor. The mobility of electrons is of a much higher order than the mobility of positive ions, so that in a fraction of a microsecond the electrons travel towards the conductor, while on the other hand, the more sluggish positive ions remain practically stationary even for much longer intervals of time. The phenomena, as the surge voltage $V$ rises and exceeds the critical disruptive value $V_o$, consist, as it were, of positive ion streamers forming and spreading out radially from the conductor and electrons moving in rapidly along the streamers to the conductor, as shown in Fig. 17A. Upon collapse of the positive surge, as shown dotted in Fig. 17C, the conductor assumes ground

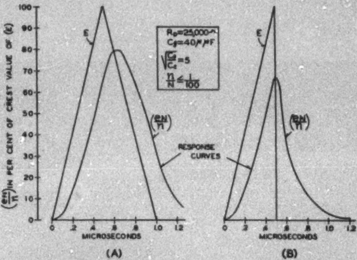

FIG. 15—RESPONSE OF RESISTANCE-CAPACITY NETWORK TO STEEP-FRONTED AND ABRUPT TAIL SURGES

potential through the surge generator circuit. A residual electrostatic field at *p* subsists, which depends on the amount of the positive space charge and the effective capacity of the space charge to the conductor and to earth respectively.

Experimental results with the capacity potentiometer, Fig. 6, show that without conductors of large radius the residual voltage recorded with positive surges is in the order of 10 per cent of the total voltage (oscillogram *A*, Fig. 10). So that, from the fact that the capacity of the space charge to the adjacent conductor surfaces is large relative to its capacity to earth, it stands to reason that for high voltages considerably exceeding the disruptive voltage $V_o$, a large percentage of the charge at the conductor is out in space. The positive space charge subsequently disappears through conduction to conductor and ground, recombination with stray electrons, diffusion, etc., in a time measured in hundreds of microseconds. Oscillograms *C* and *D*, Fig. 12, give the flashover of positive surges and also measure the residual voltage for three to four hundred microseconds after flashover. It should be noted, however, that the collapse of the residual voltage in these films is due partially to the leakage resistance across the voltage deflection plates of the oscillograph.

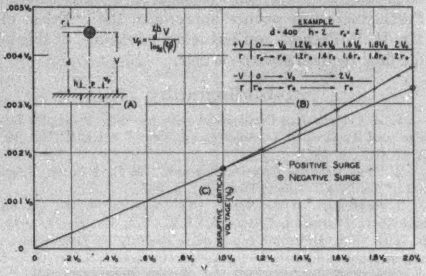

Fig. 16—Surge Potential at Point (*p*) in Electrostatic Field of Long Conductor Parallel to Earth (Dielectric of Medium Consisting of Air at Atmospheric Conditions)

*A*. Voltage $v_p$ at point (*p*) as function of effective radius (*r*) of conductor, spacing (*d*) between conductor and earth, and small distance (*h*) above earth: *V*, surge voltage applied between conductor and earth

*B*. Effective radius of conductor as function of surge voltage *V* above disruptive critical value $V_0$ and of polarity of surge voltage *V*: the variation of the effective radius with the amplitude and polarity of the surge voltage is based on approximate and simplifying assumptions—however, the striking similarity of the calculated curves (*c*) to the calibration curves in Fig. 11 is noteworthy

*C*. Calculated curves of voltage $v_p$ as function of surge voltage *V* and of polarity of *V*

The case of the negative surge *V* is illustrated in Fig. 17B. Above the disruptive critical voltage $V_o$, positive ions and electrons are generated in the air adjacent to the conductor. Under the repelling force of the negative charge on the conductor, and due to their rapid mobility, the electrons move out to the periphery, and a positive space charge is established between the conductor and the negative space charge. Thus equal positive and negative space charges are established so that the electrostatic field set up at *p* cannot be appreciably affected by the presence of the space charges. This is shown in the calibration curves of the capacity potentiometer for negative surges, Figs. 9 and 11. Upon the collapse of the negative surge, the voltage recorded drops closely to zero, as the positive and negative space charges counteract each other in a large measure. Oscillograms *B* and *D* of Fig. 10 substantiate this point.

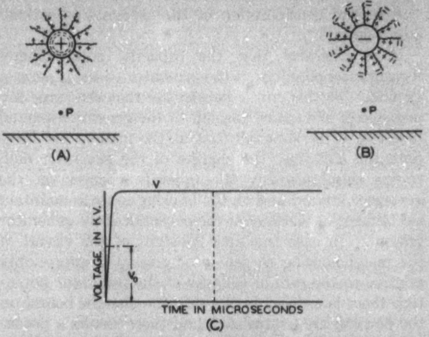

Fig. 17—Positive and Negative Surges Exceeding Disruptive Critical Voltage $V_o$ Applied Between Conductor and Earth

*A*. Schematic representation of the formation of space charge with positive surge applied to conductor and surge exceeding disruptive critical voltage $V_0$

*B*. Schematic representation of the formation of space charge with negative surge applied to conductor and surge exceeding disruptive critical voltage $V_0$

*C*. Wave of surge voltage *V* applied between conductor and earth; dotted line indicates collapse of surge voltage between conductor and earth to zero

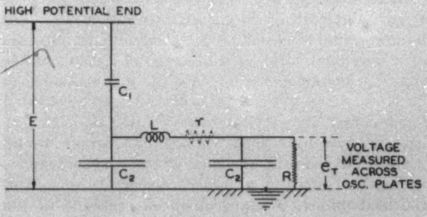

Fig. 18—Equivalent Circuit of Capacity Potentiometer

$C_1$, capacity of pick-up element to the high potential end or electrode

$C_2 + C_3$, combined capacity to ground of lead connecting pick-up element to oscillograph, of the pick-up element and of the deflection plate connecting to lead

*L*, inductance of lead connecting pick-up element to oscillograph

*R*, resistance shunted across deflection plates

Approximate values of circuit constants:

$C_1 = 0.06\ \mu\mu f$: $C_2 = 40\ \mu\mu f$: $L = 1\ \mu H$: $R = 9$ megohms

The above interpretation is in agreement with the corresponding experimental results reported, and also with the recent work of other investigators on the phenomena of surge corona and surge voltage breakdown in air.[9,10] The findings here reported bear out some of the fundamental relationships of surge corona; however, further discussion lies beyond the scope of this paper. The practical results reached bring out emphatically the necessity of large radii of curvature for all parts at high potential particularly those parts closely coupled with the pick-up element of the capacity potentiometer.

A second consideration of the capacity potentiometer follows:

It is desirable that the capacity potentiometer measure the potential of the generator to the generator ground. To this end it is essential that the surge impedance of the entire housing to the generator ground (see Fig. 6) be so small that at the instant the surge potential collapses, the charges of the generator neutralize simultaneously the opposite charges on the generator ground and on the housing so as to maintain the housing at all times at the potential of the generator ground. In case the time constant of the circuit of the metal housing to generator ground is appreciably relative to the rate of collapse of the generator potential, there is a delay in the rate the charges bound on the housing are neutralized, and there results a potential between parts of the housing and ground. These bound charges in turn induce a potential on the pick-up element; oscillations also take place. To eliminate such effects to a minimum, particular care was taken to see that all conducting parts adjacent to the pick-up element of the potentiometer were intimately connected to constitute an integral part of the true generator ground.

Next to consider is the question of response of the capacity potentiometer. In Fig. 18 is represented the equivalent circuit of the capacity potentiometer. The natural period of oscillation of this circuit is in the order of a few hundredths of a microsecond; therefore the capacity potentiometer is capable of responding to very fast surges of this time order. A resistance $r$ of a few hundred ohms or less inserted in the lead connecting the pick-up element to the oscillograph would prevent any natural tendency of the lead inductance to oscillate with the combined capacity to ground of the lead proper, of the pick-up element and of the deflection plate connecting to the lead, but this precaution is necessary only in the case of extremely fast surges of a time duration approaching the natural oscillation of the lead. The purpose of the very large resistance $R$ is to leak off to ground any extraneous charges that would otherwise accumulate across the deflection plate connecting to the lead. In this way the deflection plates are kept in proper condition for surge measurement. This resistance, if not sufficiently large, however, may also neutralize the charges induced on the plates by the surge measured. The rate at which equal and opposite charges on the plates are neutralized is given by the time constant $2C_2 \times R$, which in this case is in the order of several hundred microseconds. Therefore, the capacity potentiometer is capable of responding to extremely abrupt surges in the order of hundredths of a microsecond and, besides, it can respond in strict inverse proportionality of the capacity components even to the very longest surges that are of engineering importance both in laboratory investigations and in commercial surge tests.

## ACKNOWLEDGMENT

The author acknowledges the material aid rendered by Mr. F. J. Vogel in the preparation of this article, particularly on the part relating to the practical work of the laboratory technique. Mention should also be made of Mr. E. J. Grimmer for his assistance in the experimental work at the Sharon High-Voltage Laboratory, and due credit given to engineers of the Trafford High-Voltage Laboratory for experimental investigations there similar in some respects to those at Sharon. Furthermore, the author appreciates the criticism of Mr. H. V. Putman and has taken advantage of this in the final rendering of the article.

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11. "The Theory of Voltage Dividers and Their Use with Cathode Ray Oscillographs," M. F. Peters, G. F. Blackburn and P. T. Hannen, Bureau of Std. *Journal of Research*, July 1932.

12. This is one of the first and the simplest potential divider systems used by Gábor. Modifications of this, which however, result in complications for fundamental calibration purposes, may be found in F. P. Burch: "On Potential Dividers for Cathode Ray Oscillographs," *Phil. Mag.*, S. 7, Vol. 13, No. 86, April 1932, p. 760.

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# Discussion

## LABORATORY MEASUREMENT OF IMPULSE VOLTAGES

(Dowell and Foust)

## THE MEASUREMENT OF HIGH-SURGE VOLTAGES

(Bellaschi)

**P. L. Bellaschi:**

CRITIQUE ON METHODS OF MEASUREMENT OF SURGE VOLTAGES

The two papers on surge voltage measurement give the methods followed in each of two groups of laboratories. In view of the importance of the subject and the urgent necessity for establishing surge voltage measurement everywhere on a fundamental basis, it is well to compare in considerable detail the two methods described.

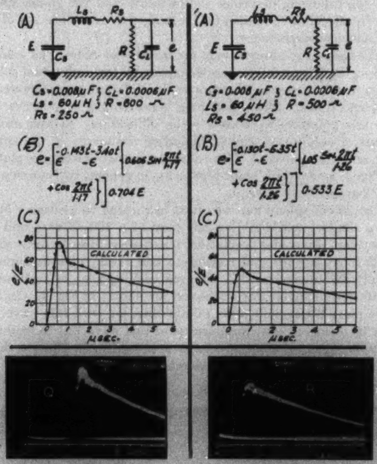
(A)
Ls
Rs
E
Cs
R
CL
e
Cs = 0.008 μF ; CL = 0.0006 μF
Ls = 60 μH ; R = 600 Ω
Rs = 250 Ω
(B)
e = [ε^(-0.143t) - ε^(-3.40t) {0.606 sin 2πt/1.17 + cos 2πt/1.17}] 0.704 E
(C)
CALCULATED
e/E
0
20
40
60
80
0 1 2 3 4 5 6
μSEC.
(A)
Ls
Rs
E
Cs
R
CL
e
Cs = 0.008 μF ; CL = 0.0006 μF
Ls = 60 μH ; R = 500 Ω
Rs = 450 Ω
(B)
e = [ε^(-0.130t) - ε^(-6.35t) {1.05 sin 2πt/1.26 + cos 2πt/1.26}] 0.533 E
(C)
CALCULATED
e/E
0
20
40
60
80
0 1 2 3 4 5 6
μSEC.
Q
R

Fig. 1

In the development of methods of surge voltage measurement at the Sharon High Voltage Laboratory and also at Trafford, the surge voltage generated and applied to the test piece or apparatus tested has been calculated. The method of calculation is fully discussed in a paper presented before the Institute in June 1932, and the determination of the surge generator constants, constants of apparatus tested, etc., is given in detail in the closing discussion of the same paper[1].

For the purpose at hand let us consider, for example, the case when the surge generator is set up to test point gaps or insulator strings with approximately a ½-5 microsecond wave. The constants of the surge generator circuit and of the test piece are:

$C_s$, capacity of surge generator

$L_s$, inductance of discharge circuit of surge generator

$R_s$, combined inherent and inserted resistance in surge generator

$C_L$, combined stray capacity of surge generator and capacity of test piece

$R$, load resistance of surge generator

$E$ voltage to which surge generator capacity is charged initially

In the left-hand column of Fig. 1 in section *A* is given the equivalent circuit for one arrangement of the surge generator and test piece, and immediately below are tabulated the numerical values of the circuit constants. From the circuit in section *A* and its complete solution[1], the surge voltage applied to the test piece is expressed by the equation in section *B*. This equation is in terms of the initial voltage *E* and of time *t* in microseconds; it is plotted in curve *C*. For the purpose of comparison the measured voltage is given below, oscillogram *Q*. The voltage in oscillogram *Q* is measured by the method described in the paper by the writer.

In the surge generator test-circuit shown in the left-hand column of Fig. 1, the inserted resistance $R_s$ was insufficient to dampen completely the oscillation superimposed on the exponential component of the wave, and therefore this resistance was increased to the appropriate calculated value, given in *A* in the right-hand column. Thus a smooth wave was obtained.

In such calculations full cognizance must be taken of all of the constants of the surge generator circuit and of the test piece or apparatus tested. This is essential if close agreement, as shown in the two examples in Fig. 1, is to be expected between calculated and measured surge voltages. But even with these precautions and care, one will note that as a fundamental method, the calculated surge voltage depends on the correct determination of the initial voltage *E* across the surge generator capacity and on accurately established circuit constants for the entire surge generator and load; and further, that the circuit constants must for the sake of practical calculation be considered as lumped. We have used successfully the complete method of calculation for determining the surge voltage generated, but *the purpose of this calculation is primarily to give further assurance and control over the correct operation of the circuits and is not intended to serve as a fundamental method of surge voltage measurement in itself.*

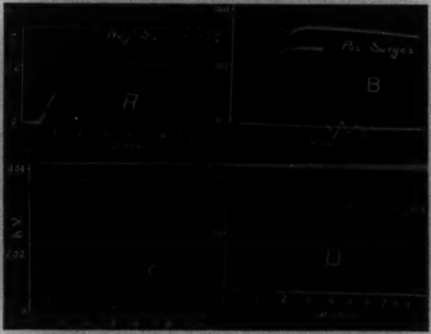

Fig. 2

The laboratories at Trafford and Sharon base the measurement of surge voltages on inherently fundamental methods. The paper presented by the writer describes the method. The resistance potentiometer as used in these laboratories responds with fidelity (both as to wave form and as to constant reduction ratio) to the laboratory waves of ½-5, 1-10, and 1½-40 microseconds. The reduction ratio of the resistance potentiometer is readily calculated from its resistance components. For still more rapid surges than the proposed standard waves, the capacity potentiometer described in the paper by the writer finds useful application. It is of interest to know that the Sharon and Trafford laboratories, each working independently on the time-lag determination of point-gaps, insulator strings, etc., using similar surge waves and methods of correction for air density and humidity, have arrived within experimental error at the same results.

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[1] *Characteristics of Surge Generators for Transformer Testing*, by P. L. Bellaschi, A.I.E.E. Trans., December 1932, p. 936.

The method of measurement described in Messrs. Dowell and Foust's paper is based on the calculation of the surge voltage from the surge generator circuit and on the sphere gap measurement of the surge voltage crest. The authors lean considerably on Mr. Peek's work. Mr. Peek in his papers[2] calculates the surge voltage generated from the surge generator constants $C_s$, $L_s$ and $R$, and from the initial voltage $E$. In fact, by this method in 1915, Mr. Peek calibrated the 25-cm sphere gap to impulse voltages up to 8-cm gap spacing, and since this calibration apparently checks the 60-cycle calibration he assumed the 60-cycle and impulse calibrations as identical up to the full diameter spacing of the sphere gap[3]. In 1929 Mr. Peek gave the spark-over curve of the 100-cm. sphere gap and the corresponding lightning generator constants ($C_s$, $L_s$ and $R$). On the basis of these calibrations Mr. Peek and his associates have insisted up to the very present on the use of the sphere gap virtually as a primary standard in surge voltage measurement, accepting the present A.I.E.E. calibration curves as applicable to surge voltage measurement.

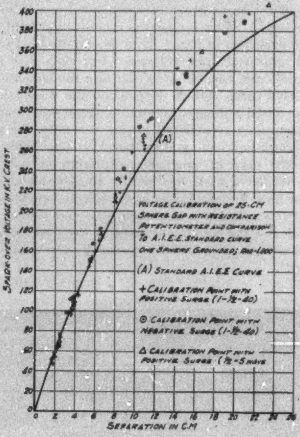

Fig. 3

Now, in the first place, we must bear in mind that in any attempt to calculate the surge voltage from the surge generator circuit and from the initial voltage $E$, at least the refinements outlined in the paper[1] previously mentioned are necessary in order to obtain reasonably correct results, more so if an attempt is made to calibrate sphere gaps to surge voltages from such calculation. We note from Fig. 1 in the paper by Messrs. Dowell and Foust that the surge generator circuit and load are actually being considered now more fully than their associates have done in the past. This is a step in the right direction, as it can be seen that from this circuit the calculated voltage is in accord with the recorded oscillogram (see Fig. 6 of the paper by Messrs. Dowell and Foust). However, if the use of the sphere gaps to measure surge voltages is insisted upon—as Messrs. Dowell and Foust and associates do—then the sphere gaps should be calibrated originally against a true fundamental standard rather than rely for their surge voltage calibration on the round-about method of doubtful rigor stated in the preceding paragraph. The resistance potentiometer, as well as a properly dimensioned capacity potentiometer, for example, lends itself inherently as a fundamental device for such calibration. *It is recommended, therefore, that sphere gap calibrations against a fundamental standard be used in the future and that the limitations of sphere gaps be clearly set forth when these are used as a standard for the measurement of surge voltages.*

### CALIBRATION OF SPHERE GAPS TO SURGE VOLTAGES

The calibration of the 200-cm sphere gap has already been fully described in the paper by the writer. As a further example, the following describes the calibration of the 25-cm sphere gap by the same fundamental method, that is, by the use of the resistance potentiometer.

The following observations are worthy of note: The calibration of the 25-cm sphere gap was made on two individual sphere gaps, in two separate laboratories, by different operators and at different times. Short and long wave surges of positive and negative polarities were used in the calibration. Sample oscillograms of calibration points, including flashovers of the sphere gap, are given in Fig. 2. The results of the calibration are plotted in Fig. 3, where each point represents in general two consecutive oscillograph measurements.

The 25-cm sphere gap was next calibrated to a surge voltage wave somewhat resembling one loop of a 100-microsecond (10 kilocycles) sinusoidal oscillation. This wave rises to crest value in 25 microseconds and recedes to half crest value in approximately 50 microseconds. Sample oscillograms of calibration points and of sphere gap flashovers are shown in Fig. 4. In Fig. 5 are plotted the calibration points obtained with this wave. It may be observed that the purpose of this wave was to calibrate the sphere gap to a surge voltage approaching in effect a single loop of the low frequency commercial voltage (60 cycle).

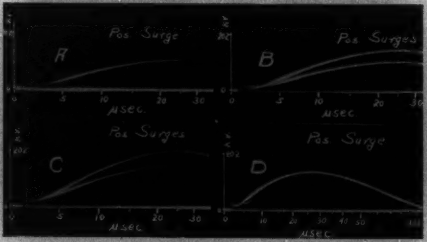

Fig. 4

The calibration points in Figs. 3 and 5 fit a calibration curve which coincides with the present standard A.I.E.E. curve up to approximately 8-cm gap separation but rises well above the A.I.E.E. curve for the wider separations.

The effect of ground and adjacent bodies on the sphere gap calibration was also investigated. Briefly: it is desirable to space the sphere gap at least several sphere diameters from vertical bodies; the grounded sphere may be spaced one to several sphere diameters above ground with no appreciable effect on calibration; the sphere gap behaves erratically at the very wide separation of one sphere diameter, in fact, it is recommended not to use it at gap separations greater than one-half sphere diameter.

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[2] *The Effect of Transient Voltages on Dielectrics*, A.I.E.E. TRANS., 1915, p. 1857.

*Lightning—Progress in Lightning Research in the Field and in the Laboratory*, A.I.E.E. TRANS., 1929, p. 436.

[3] A.I.E.E. TRANS., Vol. XXXIV, Part II, p. 1870, Fig. 9; also bottom of p. 1916.

Fig. 6 bears out a point of further interest in the fundamental calibration of the 25-cm sphere gap. This plot gives the relation between the deflection on the film due to the resistance potentiometer and the corresponding deflection due to the capacity potentiometer. The capacity potentiometer is identically the same as described in the paper by the writer, except that in the present case a pick-up element of greater sensitivity was used (2.00-inch deflection with capacity potentiometer corresponds closely to 540 kv). The plot in Fig. 6 confirms the straight line relationship between the surge voltage measured with the resistance potentiometer and the stepped-down voltage measured at the oscillograph. The resistance potentiometer used is approximately 10 feet in length and has a total resistance in the order of 10,000 ohms; this potentiometer responds rapidly even to surges of a fraction of a microsecond duration.

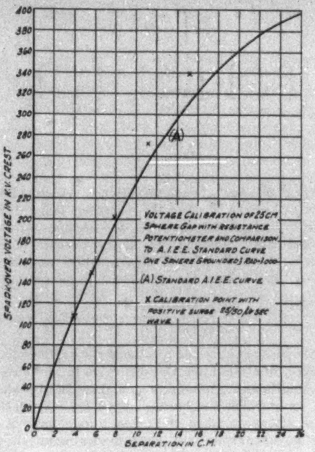

Fig. 5

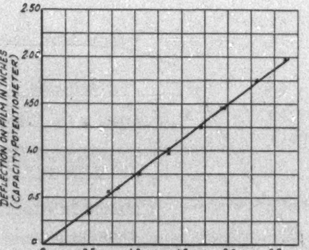

Fig. 6

### Conclusion

The first logical step in an attempt to compare results between the various laboratories is to establish universally fundamental methods of measurement. Comparison of results between different laboratories would then have more significance, apparent differences would be eliminated, and thus the probabilities of a closer agreement enhanced. *To this end we recommend the resistance potentiometer as the fundamental standard. Sphere gaps if used in surge voltage measurement should be checked for their calibration against the fundamental standard. Calculation of the surge voltage from the surge generator test-circuit is useful for control purposes but inadequate as a fundamental method of surge voltage measurement.*

**L. V. Bewley:** The essential elements of an impulse testing set-up are represented in Fig. 7. To develop a proper technique for handling such a complicated circuit, sensitive as it is to errors, is a problem of no mean proportions. Those who have carried on the work have been faced constantly with a multiplicity of vexatious and aggravating problems, among which may be mentioned:

1. The wilful idiosyncrasies of the cathode-ray oscillograph, which entitles it to be called the prima donna of electrical measuring devices.

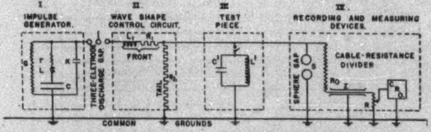

Fig. 7—Equivalent Circuit of Impulse Testing Equipment

I. $C$ = Generator capacitor units, arranged to be charged in parallel and discharged in series
$G$ = Leakage conductance of charging resistors and over-generator frame (permits leakage of charge)
$L$ = Inherent inductance in generator circuit (retards wave front and causes oscillations)
$r$ = Inherent resistance in generator circuit (retards wave front, but not appreciably)
$K$ = Terminal capacitance due to gaps, leads, etc.
II. $L_1$ = Inductance to retard wave front or to introduce oscillations
$R_1$ = Resistance to control front of wave } Depending also on I and III
$R_2$ = Resistance to control tail of wave }
III. $C'$ = Effective capacitance of test piece (affects voltage crest appreciably, depending on I and II)
$L'$ = Effective inductance of test piece (affects wave tail appreciably and introduces oscillations)
IV. $S$ = Sphere gap (measures voltage crests, except for extremely short time-lags)
$R_0$ = Resistance of divider } Determine voltage reduction
$Z$ = Surge impedance of divider }
$R = Z$ = Cable grounding resistor (potentiometer for C.R.O. $R = Z$ prevents reflections)
$CRO$ = Cathode-ray oscillograph

2. Shielding against extraneous electrostatic and electromagnetic fields.

3. Elimination of undesirable oscillations.

4. Securing good fixed grounds common to the complete equipment.

5. Evaluation of the effects of barometric pressure, humidity, temperature.

6. Calculation and predetermination of wave shapes.

7. Determination of the errors in the measuring devices.

The present papers by Foust and Dowell, and Bellaschi are concerned principally with the last of these; and are indicative of the fine work that is being done along these lines. By way of supplement, I wish to discuss the errors of the cable-type divider, and to show that these errors may either be eliminated or compensated for by proper adjustments and technique.

### Errors in Cable-Type Divider

There are four possible sources of error in a cable-type divider connected as in Fig. 8:

1. The terminal resistance $R$ is not equal to the surge impedance of the cable; due both to errors in adjustment and to the fact that a concentric cable is not a true surge impedance invariant to changes of wave shape.
2. Capacitance or other impedance of the measuring circuit.
3. Attenuation and distortion in the cable.
4. Distributed capacitance to ground of the divider resistance.

When the terminal resistance is not equal to the surge impedance of the cable, successive reflections occur; and the voltage across the resistor is given by (ignoring $C$).

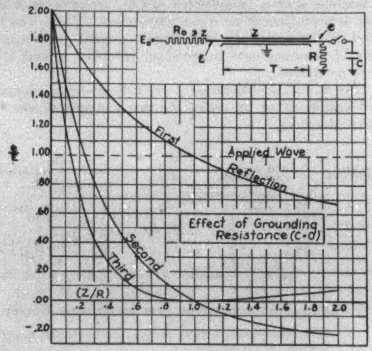

FIG. 8

$$e = \frac{2R}{R+Z}\left\{1 + (a_1a_2)_{2T} + (a_1a_2)_{4T}{}^2 + \ldots\right\}E \qquad (1)$$

where

$$a_1 = \frac{R_0 - Z}{R_0 + Z} \cong 1 \text{ if } R_0 \text{ is very large compared with } Z$$

$$a_2 = \frac{R - Z}{R + Z}$$

$E_0$ = applied wave

$$E = \frac{Z}{R_0 + Z}E_0$$

$T$ = cable length in microseconds

If $R = Z$, then $a_2 = 0$, there are no reflections, and $e = E$. Equation (1) has been plotted in Fig. 8, for the first three reflections, as function of the ratio $(Z/R)$. It is evident that a departure from $Z/R = 1$ leads to the existence of reflections and consequent error.

In Fig. 9 the error of measured wave crest and front is shown for an exaggerated case of $(Z/R = 0.6)$ and $(2T/F = 0.4)$. The effect has been to lengthen the front by 80 per cent and increase the crest by 70 per cent.

In Fig. 10 the effect of increasing the length of the cable (when $R \neq Z$) is shown for a wave which has been chopped on the front. Thus when $2T$ is less than $F$ the reflections pile up and give a measured crest much in excess of the true crest. However, as $2T$ is increased the excess decreases and reaches a constant value for $2T = F$; this residual error being the excess due to the first reflection.

In Fig. 11 the error due to terminal capacitance is shown, when $R = Z$. In this case the voltage is

$$e = \left\{\left[\frac{\alpha}{p+\alpha}\right] + \left[\frac{-p\alpha}{(p+\alpha)^2}\right]_{2T} + \left[\frac{p^2\alpha}{(p+\alpha)^3}\right]_{4T} + \ldots\right\}E$$

and if $E$ is an infinite rectangular wave this integrates to

$$e = E\left\{[1 - \epsilon^{-\alpha t}] - [\alpha t\epsilon^{-\alpha t}]_{2T} + \left[(2\alpha t - \alpha^2t^2)\frac{\epsilon^{-\alpha t}}{2}\right]_{4T} + \ldots\right\}$$

$$= E\left\{\begin{bmatrix}1.000\\ \text{Max.}\end{bmatrix} - \begin{bmatrix}0.368\\ \text{Max.}\end{bmatrix}_{2T} + \begin{bmatrix}0.230\\ \text{Max.}\end{bmatrix}_{4T} + \ldots\right\} \qquad (2)$$

where

$$\alpha = \frac{2}{ZC}$$

Therefore, the *crest* of each reflection is the same for all finite values of $C$, but the *length* of the reflection, being directly proportional to $C$, decreases therewith, and becomes extremely short in practical cases. Thus in Fig. 11 the "length" of the *second reflection* is about $\theta = 5$. If in a practical case $Z = 50$ and $C = 0.0001\ \mu f$ it follows that the length in microseconds is only

$$t = \frac{ZC}{2}\theta = \frac{50 \times 0.0001 \times 5}{2} = 0.0125 \textit{ microsecond}$$

and would pass unnoticed on a cathode-ray oscillogram.

The effect of attenuation and distortion in the cable increases with its length, and is more pronounced for short peaked waves. Thus a wave which has been chopped by a sparkover on its front will attenuate much more than a long wave of the same crest. If no other errors exist in the divider circuit, the measured wave may be several per cent too low for chopped waves. If the amount of this attenuation is known for a given cable, it can be compensated for, approximately, by making a corresponding increase in the ratio $(R/Z)$; but it must be verified that the attenuation is practically constant over the range being investigated.

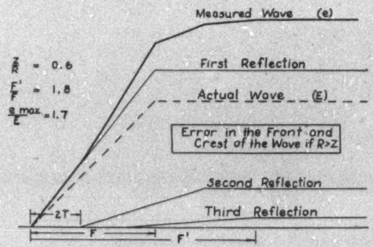

FIG. 9

The divider resistor $R_0$ undoubtedly possesses distributed series and shunt capacitance, as discussed in Bellaschi's paper, as well as series inductance. The question arises as to whether both inductance and capacitance have an appreciable influence, or does the influence of one of them predominate?

Assume in the first place that only capacitance to ground is present, and for the sake of simplicity suppose it lumped at the midpoint of the resistor. Then for a rectangular applied wave the wave entering the cable is

$$E' = \frac{Z}{R_0} E_0 \left( 1 - \epsilon^{-\frac{4t}{R_0 C}} \right) \tag{3}$$

Hence the time constant is $T' = R_0 C/4$, and since $R_0$ and $C$ increase together—*the greater $R_0$ the more retardation of wave front.*

Now if only series inductance is present, in addition to the resistance, the transmitted wave is

$$E'' = \frac{Z}{R_0} E_0 \left( 1 - \epsilon^{-\frac{R_0 t}{L}} \right) \tag{4}$$

Hence the time constant is $T'' = L/R$ and since $L$ does not increase as fast as $R_0$, as extra resistor units are added, it follows that—*the greater $R_0$ the less retardation of wave front.*

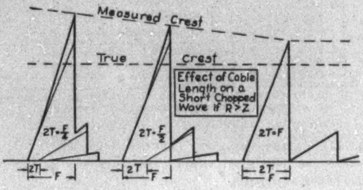

FIG. 10

But the experimental facts agree with criterion (3), which supports Bellaschi's contention of a distributed capacitance. Bellaschi has given the equation and curves for the voltage distribution along the resistor, assuming the constants to be uniformly distributed. The more pertinent information required is a knowledge of the wave shape transmitted to the cable. This is readily arrived at by solving the distributed circuit for current instead of voltage, thus

$$i = \frac{E_0}{R_0} + \frac{E_0}{R_0} \sum_{1}^{\infty} \frac{2\,(-1)^k\, \epsilon^{-\alpha t} \cos\,(k\pi n/N)}{(1 + k^2\pi^2 C_c/C_g)^2} \tag{5}$$

where

$$\alpha = \frac{k^2\pi^2}{R_0\,(C_g + k^2\pi^2 C_c)}$$

The voltage wave entering the cable therefore is

$$E = (Zi)_{n=0} = \frac{E_0 Z}{R_0} + \frac{E_0 Z}{R_0} \sum_{1}^{\infty} \frac{2\,(-1)^k\, \epsilon^{-\alpha t}}{(1 + k^2\pi^2 C_c/C_g)^2} \tag{6}$$

These equations were derived on the assumption that the current in the divider resistor is not affected by the surge impedance $Z$ of the cable, which is practically true because $R_0/Z$ is of the order of 10,000 or more.

Bellaschi remarks on the advisability of mounting the divider resistor close to the generator, and taking advantage of the electrostatic field therefrom to compensate for the capacitance to ground of the resistor. I should think that shielding in that way might be quite a delicate proposition; and possibly subject to considerable electromagnetic induction for heavy discharge currents in the generator. I understand that when the divider happens to be too close to the impulse generator discharge gap that the resistance elements are melted in two by induction; and therefore would infer that a high induction would result from too close proximity to the generator. Of course, trouble from this cause might not be serious except for heavy rates of discharge.

**J. E. Clem:** Mr. Bellaschi goes to some trouble to attempt to demonstrate that the sphere gap is not a primary standard for the measurement of voltages. I fail to see the point in this since it really makes no difference whether the means of measuring voltage is a primary standard, so called, as long as the correct results are obtained. It would be interesting to know just what faith would have been placed in the results of measurements of high impulse voltages made with a resistance cable divider had it not been for the availability of sphere gap data as a check.

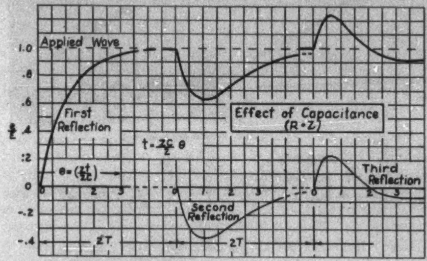

FIG. 11

Fig. 5 of this paper is very interesting since one can draw either of two conclusions from it. Either the sphere gap up to about 1,700 is correct or the resistance cable divider can be made to give correct results up to the same value. This curve further indicates that results obtained in different laboratories up to 1,700 kv upon 1.5-40 microsecond wave should check.

It is known that corona is a serious factor in producing errors in the indications of the resistance cable divider. Since the corona is a function of the voltage and also a function of the rate of change of voltage it is obvious that the corona errors would be greater for the 0.5-5 microsecond wave than for the 1.5-40 microsecond wave. From the author's Fig. 5 it is quite clear that he has been able to eliminate the corona errors for the longer wave up to 1,700 kv. It would be extremely useful if Mr. Bellaschi would show if it is possible to use the resistance cable divider as successfully for the short wave as for the long wave.

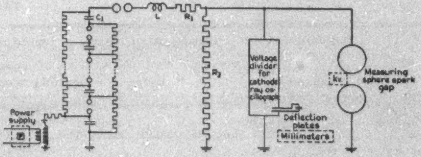
C₁
L
R₁
R₂
Voltage divider for cathode ray oscillograph
Deflection plates
Millimeters
kv.
Measuring sphere spark gap
Power supply

FIG. 12

The following discussion of the paper by Messrs. Dowell and Foust is not intended in any way to be a criticism of the material presented. Rather, it is designed to present supplementary data which were obtained during tests to obtain answers to questions which have come to my mind in connection with this work. These questions are briefly as follows:

1. Is there any reason why the cable used in the resistance cable divider should be limited to 150 ft in length?
2. Should we expect to obtain the same kilovolts per millimeter for the 0.5-5 and the 1.5-40 microsecond wave?
3. Should there be any difference in impulse generator excitation for the two waves?

4. Should there be any direct proportionality between the impulse generator excitation and the kilovolts as indicated by sphere gap or cathode ray oscillograph?

5. What polarity effects might be expected?

6. What steps have we taken to make sure that there are no unknown oscillations in the waves and which might cause improper indications of voltage by the sphere gap?

7. Is there any time lag effect on the sphere gaps?

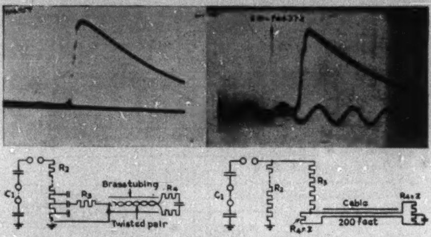

FIG. 13

(LEFT) RESISTANCE-CAPACITANCE DIVIDER COMPARATIVE OSCILLOGRAMS OF ½-5

(RIGHT) RESISTANCE-CABLE DIVIDER IMPULSE GENERATOR WAVE

The results of the investigations made to answer these questions are covered by Figs. 12 to 17:

Fig. 12 is a schematic outline of the impulse generator and discharge circuits as used in this investigation. The excitation voltage of the impulse generator was measured at the point *P* at the left. The cathode ray oscillograph with its divider and the sphere gap are located as indicated.

1. The effect of the length of the cable divider was very carefully studied and the findings may be summarized from the data given in Fig. 13. At the left in Fig. 13 is shown the wave obtained with the resistance capacitance divider and at the right is shown the same wave as indicated by the resistance cable divider. The wave at the left has been verified by calculations based on the circuit constants which were independently determined. The wave obtained by the resistance cable divider using 200 ft of cable is nearly an exact replica of the other wave. It appears then that when the proper precautions are taken there is no reason why the length of the cable divider should be limited to 150 ft.

2. Table I shows the data obtained during this investigation. Under the heading of "Sensitivity" is given kilovolts per millimeter obtained for the 0.5-5 wave and for the 1.5-40 microsecond wave. Tests were made with positive and negative polarity of each case. These data indicate that the kilovolts per millimeter is substantially the same for both waves over the range covered in the tests. It is interesting to note, however, for the difference which exists that if the calibration of the cathode ray oscillograph for the 1.5-40 wave was applied to the deflections given by the 0.5-5 wave the voltage indicated would be higher than that indicated by the sphere gap measurements.

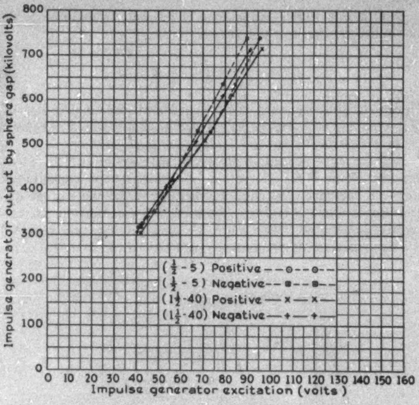

FIG. 14—CALIBRATION OF IMPULSE GENERATOR OUTPUT MEASURED BY 50-CM DIAMETER SPHERES AGAINST IMPULSE GENERATOR EXCITATION

TABLE I

| | Impulse gen. output | | Impulse gen. excitation | | | | Impulse gen. excitation | | | | Cathode ray oscillograph | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 cm diam sphere gap corrected | | Volts | | | | Corrected for circuit output efficiency | | | | Deflection millimeters | | | | Sensitivity kv per mm | | | |
| Gap setting | (½-5) | (1½-40) | (½-5) | | (1½-40) | | (94%) (½-5) | | (78%) (1½-40) | | (½-5) | | (1½-40) | | (½-5) | | (1½-40) | |
| Kv | Kv | Kv | + | − | + | − | + | − | + | − | + | − | + | − | + | − | + | − |
| 300 | 317 | 306 | 45 | 44 | 54 | 52 | 42.3 | 41.3 | 42.1 | 40.5 | 19.0 | 19.0 | 17.0 | 16.2 | 16.7 | 16.7 | 18.0 | 18.8 |
| 400 | 423 | 408 | 61 | 60 | 71 | 69 | 57.2 | 56.3 | 55.4 | 53.8 | 26.0 | 24.0 | 22.7 | 22.2 | 16.3 | 17.6 | 17.9 | 18.3 |
| 500 | 529 | 510 | 78 | 72 | 91 | 86 | 73.2 | 67.7 | 71.0 | 67.0 | 33.0 | 31.5 | 30.2 | 29.3 | 16.0 | 17.0 | 16.9 | 17.5 |
| 600 | 635 | 612 | 90 | 84 | 107 | 101 | 84.5 | 79.0 | 83.5 | 78.8 | 39.0 | 37.0 | 36.8 | 36.3 | 16.3 | 17.2 | 16.7 | 16.9 |
| 700 | 741 | 714 | 101 | 96 | 124 | 117 | 95.8 | 90.2 | 96.7 | 91.3 | 44.0 | 44.0 | 43.0 | 43.0 | 16.8 | 16.8 | 16.7 | 16.6 |
| | | | | | | | | | | | | | | | 82.1 | 85.3 | 86.2 | 88.1 Sum. |
| | | | | | | | | | | | | | | | 16.4 | 17.1 | 17.2 | 17.6 Ave. |
| | | | | | | | | | | | | | | | 16.7 | | 17.4 | Ave. |

Circuit Constants

| | (½-5) | (1½-40) |
|---|---|---|
| $C_1$ | 0.0098 μf | 0.0098 μf |
| $C_2$ | 0.000075 μf | 0.000125 μf |
| $L$ | 50 microhenrys | 0 microhenrys |
| $R_1$ | 0 | 950 ohms |
| $R_2$ | 450 ohms | 3800 ohms |

3. The impulse generator excitation required for the two waves is given in the center of the table under the heading "Impulse Generator Excitation." Due to the different constants of the circuit the impulse generator excitation efficiency is different for the two waves. When the impulse generator excitation has been corrected for discharge circuit output efficiency, it is found that practically the same excitation is required for either wave.

4. This tabulation also indicates that the impulse generator excitation is practically directly proportional to the voltage as measured by the sphere gap or by the cathode ray oscillograph. This is evident from Fig. 14.

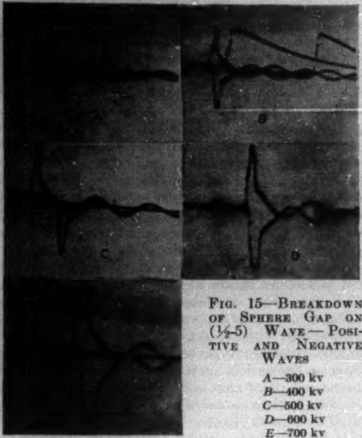

Fig. 15—Breakdown of Sphere Gap on (½-5) Wave—Positive and Negative Waves

*A*—300 kv
*B*—400 kv
*C*—500 kv
*D*—600 kv
*E*—700 kv

5. The effect of polarity is evident from this same tabulation where it is seen that positive polarity voltage for either the short or the long wave required constantly a higher impulse generator excitation. There seems to be no great difference in sensitivity of the cathode ray oscillograph for positive and negative polarities. In Fig. 15 is shown a set of oscillograms taken over a range of voltages with positive and negative voltage applications. There seems to be no difference in the flashover characteristics of the spheres between the positive and negative waves over the range of voltage investigated.

6. In Fig. 16 is shown a set of oscillograms made to demonstrate that only known oscillations are present in the applied voltage. The upper oscillogram shows the wave without any capacitance load. This wave has previously been verified by measurement and by calculations based on circuit constants which were independently determined. In the second oscillogram the capacitance load is due to a 50 cm diameter sphere, as shown. The oscillations appearing on this wave were predicted and checked quite well with the prediction. In the third and fourth oscillograms an increasing capacitance load has been added. In each case the oscillations were predicted and agreed reasonably well with the predictions. Since these small oscillations are only present when they should be and have been predicted and observed it seems very reasonable to believe that no others are present.

Further investigations along this line were made with a much larger capacitance, used so that the oscillation would be of much greater amplitude. These are shown in Fig. 17. In this case also the superposed oscillations were predicted and the predictions agreed quite well with the measured values. Oscillograms are given in which flashover did not occur and in which flashover did occur. It should be noticed that a very slight increase in excitation is required to cause flashover.

7. The sphere gap seems to be showing some time lag at 500 and 600 kv. (See Fig. 17.) At 500 kv a series of films was taken from an excitation of 62 and 57 volts to 65 and 60 volts inclusive. (See Fig. 17.) It was found that an increase in excitation of only 2 volts was sufficient to cause the apparent time lag to disappear, thus indicating that the voltage adjustment giving a time lag for the spheres is very critical, and therefore the error from this source is quite small.

It is very possible that the resistance divider may show polarity effects due to difference in corona at higher voltages and that this same effect might cause the proportionality between excitation and voltage to change, and further, the corona effect might also introduce different errors for the short wave and for the long wave.

It should be noted that all the foregoing tests were made at or below 700 kv, and that 700 kv is pretty well up toward the limit for the 50 cm spheres used in this investigation. Sphere gaps used for impulse voltage measurements should have a lower permissible ratio of spacing to diameter than when used for 60-cycle measurement. With these reservations in mind, the following general conclusions, applicable below 700 kv, may be drawn from the data here presented:

Resistance cable dividers can be made to give correct results with a cable up to 200 ft by the development of proper technique. The longer cable requires more careful adjustment.

The same kilovolts per millimeter for the 0.5-5 wave should be obtained as for the 1.5-40 wave.

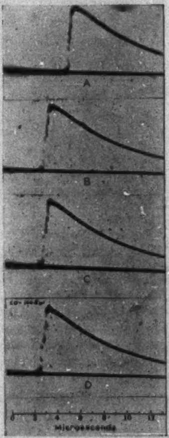

Fig. 16—Impulse Generator Test Wave (½-5) Showing Oscillations Caused by Low Capacitance Loads

*A*—Circuit without capacitance load 700 kv crest
*B*—with 50-cm diam. sphere spark gap load
*C*—with 50-cm gap and 3 pedestal units
*D*—with 50-cm gap and 3 pedestal units and 7 unit

After corrections for discharge circuit efficiency have been made, the same impulse generator excitation should be obtained for the short wave as for the long wave.

Direct proportionality exists between the impulse generator excitation and the output voltage whether the voltage is measured by sphere gap or by cathode ray oscillograph deflection.

Higher impulse generator excitation is required for positive polarity than for negative polarity for both the long and short waves. Over the range of voltage tested there was no appreciable difference in the sphere gap indication or in the kilovolts per millimeter due to polarity.

Study of oscillations indicate that our laboratory has sufficient mastery of impulse test technique that we are sure there are no unsuspected oscillations.

The possible error due to apparent time lag of the sphere gap is quite small, and, in general when sphere gaps are used for measurements of impulse voltages, the range should be more limited than when used for 60-cycle measurements.

**F. D. Fielder:** The paper by Mr. Bellaschi represents much research, and corroborates parallel work at Trafford.

In our capacity divider studies at Trafford, we were handicapped by unfavorable ground conditions. Parts of the capacity system which should remain at zero potential acquired oscillatory voltages of the order of hundreds of volts for short times, thus introducing serious oscillations. These were finally eliminated to a great extent by the use of balanced capacities. Briefly, to the same extent that fluctuations in the ground plate influenced the pickup electrode which was directly connected to the front oscillograph voltage terminal, these influences were balanced with a pickup electrode located behind the ground plate and connected to the rear oscillograph terminal. With this device the waves became recognizable, and the same characteristics of positive and negative calibrations were found as reported in the paper. The same explanations were assigned to the behavior and the same methods of improvement were effective. In general, however, the use of a capacity divider for high voltages is not as suitable at Trafford, because all the apparatus, including the test piece, are close together in the same building, thus introducing complications due to the leads.

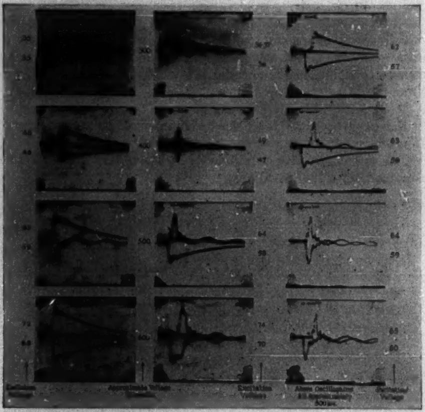

FIG. 17—SPHERE GAP VOLTAGE MEASUREMENTS ON ½-5 WAVE WITH SUPERIMPOSED OSCILLATIONS SHOWING IMPULSE GENERATOR EXCITATION VOLTAGES

In using the resistance cable divider system, it is necessary to have all parts of the system in proper order, as error in any part leads to dissatisfaction with the system as a whole. The use of a poorly insulated cable is an example, for then the wave becomes modified as it is transmitted through the cable. If a poor cable is used it becomes necessary to employ short lengths, thus losing the convenient time delay that a long cable provides. Likewise a resistance unit which has inductance, or which has too great a total resistance, or even too great a resistance per unit length, or which has high capacity to space; all of these factors lead to error and general dissatisfaction. However, a correctly operating resistance divider is trouble free, faithful and consistent. I might suggest that Mr. Bellaschi state more fully the justification for selecting the capacity-to-space values presented in Fig. 14. It would also be interesting to extend this group of curves for resistances lower than 25,000 ohms, since most practical dividers are below this figure.

At present it is believed that resistance divider measurements for all minimum flashover voltages, and for all time lags in excess of one microsecond are reliable. For flashovers at high voltages occurring in shorter times, further improvement will be necessary. Present resistance dividers become inaccurate in this range; capacity dividers with long leads have an undesirable lead effect; capacity dividers with short leads may have variable calibrations because of corona on the leads. The solution for this requirement either is a completely shielded resistance divider, or a capacity divider so constructed that the corona from short leads and a close test piece can have no effect on the capacity relationships. A parallel plate capacity system which is sufficiently large to shield external influences completely has been suggested.

**F. D. Fielder and P. H. McAuley:** We recognize many of the problems in the paper by Messrs. Dowell and Foust which we have encountered, and although some of the solutions are similar, there remain many in which our point of view is different.

We do not agree that suitable voltage dividers for surge measurement are not available. A divider of the type designated resistance-cable in the paper has been used successfully at Trafford for over 4 years. The effects of distributed capacity, of terminal surge impedance and of cable characteristics were investigated and found satisfactory for general surge testing before its adoption. Our experience indicates that if a paper-insulated cable of at least 10,000-volt rating is used, the distortion is negligible even with a length of several hundred feet.

In our studies of different types of voltage dividers it has been found that, unless precautions are taken, resistance dividers tend to lengthen the time to the crest of the wave, and also with short waves the tendency is to reduce the crest values. In general, capacity dividers tend to introduce oscillations of more or less seriousness, and again, unless precautions are taken, a change in the calibration constant is possible. The type of divider designated as resistance-capacitance introduces the undesirable features of both types. We are inclined to question the advisability of using damping resistances in measuring circuits.

The authors completely ignore a valuable check of the accuracy of their measurements. The cathode ray oscillograph has a definite calibration constant for its deflecting plates, usually about 250 volts per centimeter deflection. It depends only on the mechanical design and on the cathode voltage, and can be determined with a high degree of accuracy by taking films with measured d-c voltages on the deflecting plates. Hence, knowing the divider ratio and the oscillograph constant an independent method of voltage measurement is available.

We are pleased to note that the authors have concluded that the rate of rise of standard waves has practically no effect of the flashover values. This was the conclusion we expressed in a discussion[4] at the 1930 Summer Convention, in which we took issue with Mr. Peek's formulas for surge breakdown of apparatus.

In the paper the viewpoint is expressed that the sphere gap is, and has been, the standard of voltage measurement, while the use of the oscillograph presents many problems, in particular concerning the voltage divider. Our viewpoint is exactly the opposite, for we feel that it is vitally important to secure accuracy of the oscillograph, before the sphere gap can be used with confidence. This follows directly from the following facts, which combine to mislead the user of sphere gaps:

1. The natural tendency of any surge generator is to produce waves with superimposed oscillations on the crest of the wave.

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[4] A.I.E.E. TRANS., October 1930, p. 1502.

2. The tendency of resistance-type dividers is to eliminate or reduce these oscillations.

3. Calculations which neglect certain of the circuit constants also eliminate or reduce these oscillations.

4. Small oscillations on the crest of the wave generally have no effect on apparatus flashover.

5. Sphere gaps, however, detect the full crest of superimposed oscillations, unless they are extremely fast.

6. The relative magnitude of the oscillation or overshooting varies with the capacity of the apparatus under test.

We believe the best way to check results, and to obtain confidence in measuring methods is by direct comparison between different types of voltage dividers; if calculations are to be used at all they should be as rigorous as possible and should neglect none of the circuit constants unless it is proved they have no effect. Calculations should not be submitted as proof that the recorded wave is a replica of the actual wave. This is particularly true when certain of the circuit constants are neglected as suggested by the authors in Fig. 3. Oscillations are due to the series inductance and stray or load capacity. When either is neglected as in Fig. 3, nothing but a smooth wave—the difference of two exponential functions—can be obtained by calculation. Except for showing the approximate front and tail such calculations are of little value. Bellaschi has developed more accurate methods for calculating wave shapes. However, additional oscillations are invariably present on the oscillograms and if overshooting occurs the oscillogram usually shows less than the calculated wave. One feature of oscillograph work which can readily be improved is the wide beams shown in Fig. 4. Assuming 1,000 kv applied these traces are nearly 100 kv wide which limits the accuracy of analysis.

A careful direct comparison of the resistance divider and 500 mm sphere gap has been made recently at Trafford. Fig. 18 shows that the calibration on both positive and negative 1.5-40 waves is different from the A.I.E.E. standard curve. It is appreciated that this statement is based on the assumption that the divider is accurate. However, apart from voltage values, it is far easier to understand a polarity effect on a gap than on a resistance. Similar tests now nearly completed indicate that the 750, 1,000 and 1,500 mm gaps have similar characteristics. This condition has great significance in connection with voltage measurement.

We do not believe the method presented for the determination of the surge impedance of cables is reliable, since it assumes perfect performance of the resistance divider. Bellaschi has shown that such performance is not to be expected for the type of waves illustrated in Fig. 15 of the paper. If the divider is in error then the surge impedance determination will also be in error. We believe a better method is the use of a low voltage surge which can be recorded with the oscillograph as it enters and as it leaves the cable. When these waves are identical the surge impedance is correct.

We would subscribe to the elaborate methods of presenting data if we thought much was to be gained by their use. However, it appears that Table II concerns itself mostly with the application of correction factors which are generally accepted and universally applied. A general statement showing the correction factors used should be sufficient, for it is to be assumed that anyone concerned with surge testing can properly apply the corrections. It is our belief that the causes of the differences between laboratories lie far deeper than simply in the working up of data.

**C. M. Foust:** Mr. Bellaschi's experience with the capacitance voltage divider is very interesting. On first thought, series capacitors always appear to be ideal for obtaining division of high voltages for measurement purposes, particularly for short-time surges. On closer examination, however, many difficulties are revealed. If air dielectric is used as Mr. Bellaschi has done space requirements often make the setup impractical and when measurements appear inconsistent, disturbances in the field between the capacitors are frequently suspected. The polarity difficulty illustrated in Figs. 9 and 11 is one such disturbance. The author chooses to explain this effect in terms of space charge and probably it is clear to many on this basis. The following viewpoint, however, is more significant and may prove helpful to others:

A capacitance voltage divider to hold true ratio must be so arranged that the series capacitor units retain constant capacitance values at all measurement voltages. In neither capacitor must the dielectric break down partially when voltage is applied. If such a partial breakdown occurs in one of the series capacitors, a higher capacitance value is obtained for this unit and an abnormal shift of voltage to the second unit occurs. This shift of voltage with partial breakdown would give the calibration characteristic shown in Fig. 11. It should be present for both polarities but to a much greater degree with positive polarity as the positive breakdown streamers are much greater in extension than negative streamers.

It must be remembered that the actual capacitance coupling values between the high voltage terminal and the pickup antennas connected to the oscillograph plates are very small. With a 1,000 to 1 voltage reduction ratio and an excess capacitance of 1,000 $\mu\mu$f across the deflection plates this capacitance coupling would be only 1 $\mu\mu$f, a very low value and difficult to work with where spacings are so great.

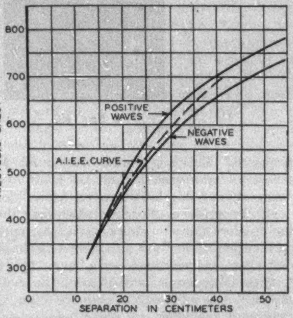

Fig. 18—Calibration Curves for 50-Cm Sphere Gap

One sphere grounded for surge voltages, 1½-40 $\mu$sec waves

The space charge viewpoint I believe of much greater value in connection with the explanation for the oscillograph trace not returning to zero for the positive polarity as shown in Fig. 10.

The use of the large shields effectively reduced the divergence between positive and negative polarity calibration curves. It appears to me, however, that such shields have several important disadvantages. Although the capacitance between the shields and the pickup elements is small still the total capacitance of the shields to ground is large. Such a large capacitance connected to the discharge circuit increases oscillatory effects in the discharge wave and makes it difficult to obtain the more rapid rates of voltage rise across the test specimen.

**C. F. Harding and C. S. Sprague:** Fig. 2 of the paper by Messrs. Dowell and Foust illustrates the relative shapes of calculated waves which conform to the definitions of the proposed standard waves. It is evident that the figures ½, 1, 1½ are scarcely representative of the actual steepnesses of the major part of the fronts of these calculated waves. It would appear to be desirable to define the front of the wave by some more representative figure, perhaps, as has been suggested, by the time between the points on the wave front corresponding to 10 per cent and 90 per cent of the crest value.

The resistance-capacitance divider of Fig. 5 is subject to the same fundamental limitations as is the resistance cable divider of Fig. 7. Of course by tapping off across a low value of resistance, the voltage impressed on the oscillograph circuit is kept low. Consequently the charging current into this circuit may be kept to a very small fraction of the total discharge current thus helping to maintain the proportionality at the higher frequencies and steeper waves. The particular disadvantage of this scheme is that when tapping off the discharge resistor at low potentials, the effect of any induced or stray pickup voltage is proportionally increased. Thus it is absolutely essential that the series capacitance, the resistance $R_3$ and the leads to the oscillograph be extremely well shielded from stray fields.

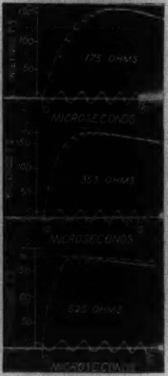

Fig. 19

Fig. 6 provides oscillograms which show the effect of the damping resistors and also of the load capacitance on the oscillations on the front of the wave although, with the slow sweep used, it is difficult to analyze these oscillations. It is desired to point out a source of apparent oscillations on the front of the wave which evidently has not received much attention. In brief, the generator circuit, including any added inductance, has a certain surge impedance, and for a given voltage a corresponding current wave will travel toward the discharge resistance. Reflections then take place across this discharge resistance in a manner entirely analogous to the reflections at the end of a transmission line grounded through various values of resistance, the major difference being that in the case of the generator circuit the distances are much shorter. Hence with a high value of resistance it is possible to get positive reflections and the voltage overshoots across the discharge resistance. With lower resistances negative reflection occurs and the rise of voltage on the front is characterized by the corresponding stair steps. In the usual case the reflections are negative rather than positive. The oscillograms in Fig. 19 were taken with the circuit adjusted to emphasize these negative reflections and to illustrate the progressive changes in these negative reflections as the discharge resistance is increased. These waves, of course, would not be used for testing. The dotted curves indicate the calculated waves. A good agreement is obtained except for the stair steps on the front; this could not be expected when the calculation is based on the assumption of lumped constants. Reflections of this sort will often be combined with oscillations of the generator inductance and load capacitance, and sometimes even with oscillations in the potentiometer circuit. The reflections across the discharge resistance, when present in a noticeable amount, can be detected by comparing their frequency with the length of the generator discharge circuit; an accurate check requires that the wave front be recorded with a sweep noticeably faster than that ordinarily used and for the steeper waves it is necessary that the potentiometer circuit constants be such as will transmit these rapid changes to the deflecting plates, without excessive damping.

Mr. Bellaschi is to be commended on his analysis of the various factors on which depend the strict proportionality of the voltage applied to the deflecting plates of the oscillograph. Quantitative data presented show the distortion due to the use of the resistance-cable divider. These data indicate that, when properly employed, the resistance-cable divider may be used without appreciable error for recording waves, having the average rise of the steepest part of the front taking place in 1 microsecond or more. For faster waves it seems desirable to use the capacitance divider. The latter, of course, must be calibrated by the sphere gap, whereas the resistance-cable divider may be checked both by the gap and by the resistance ratio.

Fig. 4D, apparently indicates a rather serious time lag of the 200-cm sphere gap on a long-tailed, flat-topped wave. This, of course, indicates the necessity of using this type of wave for the purpose of calibrating the oscillograph. In some cases voltages are measured by the sphere gap on waves having breakdown on the front or otherwise having a high peak of short duration. For work of this nature it is necessary that the sphere gap have a negligible time lag. The curves in Fig. 20 illustrate the effect of varying the intensity of ultra-violet light on small spheres at small spacings. The wave used was rather sharply peaked and accentuated the effect of the light in reducing the time lag of the sphere gap. It is reasonable to believe that the use of ultra-violet light on the larger spheres would result in more accurate measurement of the sharply peaked waves.

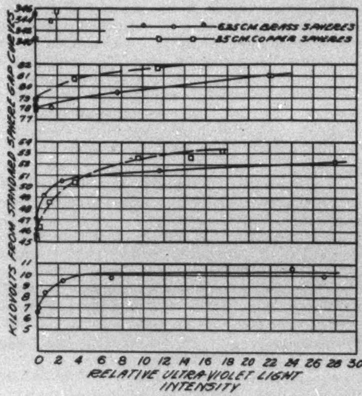

Fig. 20

Taken as a whole the data in this article appear to be in favor of the use of the capacitance potentiometer, assuming the use of the suggested static shields, and providing that oscillations in the potentiometer circuit are prevented by a sufficient, but not too high value of damping resistance.

**E. S. Lee:** Remarkable advances have been made since the year 1925, when papers were presented to the Institute on the subject of surge-voltage measurements, to the present day when papers on the subject are presented for the first time under the auspices of the Committee on Instruments and Measurements. With reference to the Bellaschi paper and the Dowell-Foust paper, I welcome this subject to the auspices of this committee. In this connection there are questions of active interest relative to sphere-spark gap calibration and use, resistance multiplier, voltage dividers, cathode-ray oscillograph performance, and the like, brought up by the report of the lightning and insulator subcommittee that are in the province of the committee on instruments and measurements and in which they should be active in progressing.

In conclusion reference is made to the heritage of the instrument engineer, which is rich. The program today shows prominence in two important fields, which is typical. No engineer advances far before he has to measure something. Thus the instrument engineer finds himself at the outer of all paths. May he continue to realize his responsibilities and the opportunities for his contributions and achievement.

**W. L. Lloyd, Jr.:** The resistance potentiometer and the capacitance potentiometer have both been used to a considerable extent in the Pittsfield High Voltage Engineering Laboratory where the capacitance potentiometer was the first type employed. While the capacitance potentiometer has certain advantages, particularly at the lower voltages where corona can be prevented, it has certain inherent disadvantages at all voltages. If the capacitance potentiometer is inclosed, difficulty is experienced in preventing oscillations on the measured wave and in maintaining the potentiometer and the oscillograph grounds at the same potential. If of open construction, as for example in the potentiometer at Sharon as described by Mr. Bellaschi, it is subject to these same oscillations and, in addition, to changes in the calibration as the capacity relationships between the exposed parts are altered for the different tests.

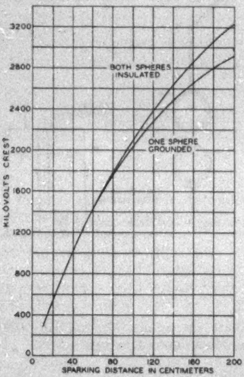

FIG. 21 — CALIBRATION CURVES FOR 200 CENTIMETER SPHERES

Mr. Dowell and Mr. Foust have given in their paper a detailed description of the precautions necessary for the accurate measurement of high voltage, short time impulses. As a result of much painstaking research, it was found possible to obtain accurate oscillograms of the high voltage test-wave and the *same calibration* for either the long or short wave. If the same calibration is not obtained with the 0.5-5 or 1-5 wave as for the 1.5-40 wave it is a clear indication that the oscillograph is not accurately following the voltage being applied to the sphere-gap and test-piece. Either the potentiometer or sphere must be wrong and the accuracy of sphere gap in sparking over without appreciable time lag on the crest of either the short or long wave cannot be questioned. Messrs. Dowell and Foust present data showing that the sphere gap has negligible time lag unless the gap is subjected to very high over-voltages and fronts considerably faster than those of the 0.5-5 or the 1.5-40 waves.

A linear calibration of voltage *vs.* oscillograph deflection is proof that the potentiometer is independent of the rate of voltage rise on the front of the wave. Therefore, changing the test wave from a 1.5 $\mu$sec front to a 0.5 $\mu$sec or 1.0 $\mu$sec front ought to give the same constant value of kilovolts per inch of deflection. Where different calibrations were obtained with the long and short waves, we found that the oscillograph was not accurately following the voltage applied to the sphere-gap and test piece.

Careful adjustments made in the oscillograph potentiometer circuit finally gave the same calibration with the short and with the long wave, and when this was obtained it was found that the oscillograph was truly portraying the impulse wave. Changes made in the lightning generator circuit then resulted in the proper changes in the measured oscillogram and the measured test wave then agreed with the calculated test wave. I would recommend the careful study of the Dowell-Foust paper by anyone planning the accurate measurement of high voltage impulse waves.

Fig. 21 shows the 200-cm sphere gap curve which has been used for a number of years in the laboratory at Pittsfield. It was calculated by means of Peek's sphere gap formula and checked by comparison with the 75 cm and 100 cm sphere gaps for both 60 cycles and impulses.

**F. W. Peek, Jr.:** It is frequently difficult to determine whether a true resistance at low frequency is still predominately a resistance or has become predominately an inductance or a capacitance under transient conditions. For this reason it is futile to argue that any type of divider for measuring impulses is a primary standard. Certain corrections must be made in all cases. Sometimes these corrections are difficult to determine. This is especially so at high voltages where the ratio is high and corona may be a factor. Polarity correction may also be necessary in the oscillograph. It is also futile to argue whether the sphere gap is a primary or secondary standard. This follows because it is sometimes necessary to make corrections in using the sphere gap. For example, for measurements on the rising front of very steep waves it may be necessary to make corrections for time lag although the time lag correction is negligible for the usual waves. However, at very high voltages possible sphere-gap errors are likely to be smaller and corrected with greater certainty than divider errors. In my work I have used the sphere where possible at moderate spacings, generally less than half diameter, thus minimizing corrections for both polarity and time lag. We must always recognize the shortcomings of any instrument and use it in such a way that probable errors are at a minimum.

While the sphere gap probably still is the most useful instrument in general measurements of impulse voltages, in the pioneer work it was invaluable. There was no other method. In fact, practically all of the time lag characteristics now determined by the cathode ray oscillograph were originally determined by the sphere gap in our early work.[5]

**E. J. Wade:** My experience with cathode ray oscillographs in the Lightning Arrester Laboratory at Pittsfield extends back to 1924 and I agree with Mr. Bewley that the idiosyncrasies are legion. However, it is a never-ending source of satisfaction to work with an instrument which, because of its extreme sensitiveness to short time phenomena, continually presents new problems.

One of the major considerations in the operation of the oscillograph is the question of obtaining a really satisfactory voltage divider. The ideal voltage divider would be one with extremely high impedance with a constant and easily measurable ratio and perfect fidelity of reduction. Unfortunately these requirements are incompatible and a compromise must always be made.

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[5] *The Effect of Transient Voltages on Dielectrics—I*, by F. W. Peek, Jr., A.I.E.E. TRANS., 1915, Vol. 34, p. 1857.

Various designs of air and oil insulated capacity dividers have been used with good results but I have always felt the lack of a direct method of determining the ratio to be a disadvantage. Also while the fidelity of reduction is unquestioned the addition of any capacity across the test piece is undesirable with some circuits, particularly where the current following breakdown is being measured.

Another voltage divider which we have found very useful is what we call the compensated resistance divider, where capacity is added to balance the error caused by the capacity of the deflecting plate circuit. One form of this divider was described by K. B. McEachron in *Electric Light and Power*, May 1929, and it is also considered mathematically by Peters, Hannen and Blackburn.[6] The advantage of this type of voltage divider is that the ratio can be accurately predetermined and the impedance made very high. Unfortunately it must be used close to the oscillograph as the introduction of a cable prevents the use of the compensating capacity.

The cable divider probably is the most widely used and valuable type of divider. Although it cannot perfectly b ecompensated the error can be made so small as to be negligible in most cases. The capacity divider and cable divider have been checked one against the other, both in the laboratory and during field tests. With either divider the connection to the oscillograph is of importance, the ground lead to the oscillograph and deflecting plates being kept as short and direct as possible, to avoid inductive drop.

**J. C. Dowell and C. M. Foust:** Mr. Bellaschi feels that the authors are appreciably in error by using the sphere gap to measure surge voltages. We would like to call attention to Fig. 5 in Mr. Bellaschi's paper showing a voltage calibration of the 200-cm sphere gap with the resistance potentiometer together with the calculated curve for the sphere gap. This apparently is a perfect check of the 200 cm sphere gap on the 1½-40 μsec wave, and it would seem that this behavior of the sphere gap would allay any criticism of its accuracy on this wave. The authors have found no appreciable difference in the operation of the sphere gap between the ½-5 and the 1½-40 waves.

While apparent time lags are occasionally recorded on oscillograms as Mr. Bellaschi has shown in Fig. 4D, it has been demonstrated by the authors that this time lag occurs only at the very minimum breakdown voltage and a very slight increase will cause it to disappear. In a sphere gap voltage calibration obtained by the authors the sphere gap is adjusted through the range from 0 to 100 per cent arcing. The mid point of this range or the 50 per cent arcing point is chosen and this is independent of the apparent time lag as mentioned above.

If by chance the sphere gap should have a time lag characteristic it would require a higher voltage to arc over a given spacing with the ½-5 wave than with the 1½-40 wave, the same as is experienced with the rod gap but to a lesser degree. Then in measuring a given applied voltage on the ½-5 wave the sphere would have to be closed down to a smaller spacing to obtain 50 per cent arcing than would be necessary if the sphere did not have a time lag. Reading the equivalent voltage from the calculated curve for this smaller spacing gives a smaller voltage than would be obtained if the sphere had no lag. Since the sparkover voltages of insulators and rod gaps for the ½-5 μsec wave obtained by the authors with the aid of the sphere gap are very appreciably higher than values obtained by other laboratories, it seems preposterous to try to explain the difference by inaccuracy of the spheres on the shorter waves since any such error would be in the wrong direction.

Mr. Bellaschi recommends that the resistance potentiometer be used as the "fundamental standard" for measuring impulse voltages. The authors' views on this point are clearly set forth in Mr. Peek's discussion. We feel that the true ratio of the resistance potentiometer is not necessarily the ohmic ratio and that it should not be relied upon as a fundamental standard for measuring kilovolts. From data that have been obtained we have reason to believe that corona affects the ratio of the resistance divider and that this effect is different for the two polarities.

Mr. Fielder and Mr. McAuley suggest an inaccuracy in the method used to measure the surge impedance of cables on account of errors in the divider for the type waves that were used. If the resistance divider cannot be made to reproduce correctly a wave with a superimposed oscillation we do not understand how it can be used with confidence in measuring kilovolts.

The authors are somewhat puzzled over Mr. Bellaschi's hesitancy regarding the use of the complete discharge circuit analysis for voltage measurement in view of his eagerness to make a strong case for the resistance voltage divider. The authors did not recommend discharge circuit analysis as a method of voltage measurement or the use of a resistance divider not checked against a sphere gap for such measurements. As pointed out by Mr. Fielder all parts of the resistance-cable divider must be in proper adjustment. High loss cable, inductance in the resistance unit, too great resistance per unit length, high capacity to space and corona all prevent good divider performance. These and others also are the identical problems which must be met in discharge circuit analysis. It easily follows, therefore, that performance of the resistance divider is quite as difficult to anticipate as that of the discharge circuit.

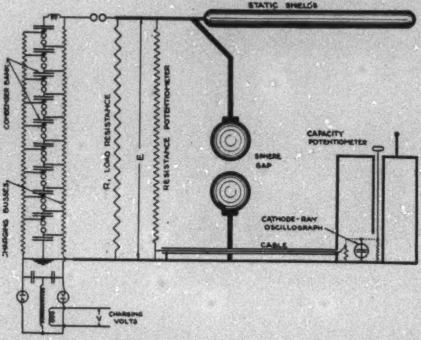

FIG. 22—SCHEMATIC DIAGRAM OF SURGE GENERATOR AND SURGE-VOLTAGE MEASURING DEVICES

**P. L. Bellaschi:** There is a consensus of opinion expressed in the above discussions to the effect that considerable progress has been made lately in the technique of surge voltage measurement. While it is gratifying to know this, we urge that the profession continue and endeavor to establish the technique of surge voltage measurement on a common and fundamental basis. The following is a resumé and answers the various points brought out in the discussions.

1. *Relationship between Surge Generator Excitation and Surge Voltage Generated.*

Fig. 22 shows schematically the exciting apparatus, the surge generator discharge circuit, and the measuring devices. Control and synchronizing circuits have for simplicity been omitted. The relationship between charging voltage $V$ and the maximum surge voltage generated $E$, for positive and negative polarities, is given in Figs. 23 and 24. These are the curves obtained at the

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6. "The Theory of Voltage Dividers and Their Use with Cathode Ray Oscillographs," *Bureau of Standards Journal of Research*, July 1932.

Sharon laboratory[7]; the lines are straight and, if projected, intersect the charging volts scale at a point slightly beyond zero. These curves demonstrate that the excitation required for a positive wave voltage is somewhat higher than for the corresponding negative wave voltage. Mr. Clem's conclusion on this matter is in agreement with our results. Consideration of these results and of the surge generator constants obviously lead to another conclusion by Mr. Clem stating that, "After corrections for discharge circuit efficiency have been made, the same impulse generator excitation should be obtained for the short wave as for the long wave."

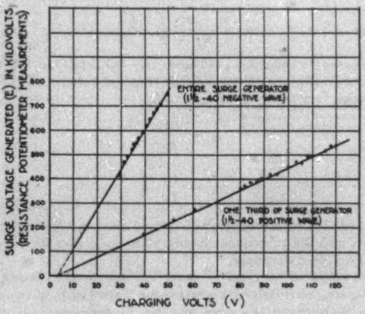

FIG. 23—RELATION BETWEEN CHARGING VOLTS ($V$) AND SURGE VOLTAGE ($E$) APPLIED TO TEST PIECE (TEST BETWEEN ELECTRODES IN OIL)

For a given set-up of the surge generator the excitation voltage affords the only means whereby the surge voltage generated can be controlled and adjusted. The relationship between the surge generator excitation and the surge voltage generated may be used as supplementary to the surge voltage recorded by the measuring devices, in so far as it is a question of securing consistent results, but there is no good reason to justify its use as a basis for fundamental measurement.

### *2. Characteristics of Surge Generators—Calculations of Surge Voltage.*

This subject has been considered at length in the foregoing discussion; little more need be added. Calculations of the surge voltage are useful in that they give an intimate understanding of the characteristics of the surge generator discharge circuit and hence give more confidence in the technique of measurement. However, while the calculated surge voltage undoubtedly serves as a useful guide, it is preposterous to expect the calculated results to be an absolute and complete confirmation of the actual surge voltage. It is obvious then that only through a reliable technique of surge voltage measurement can correct results be obtained. Our criticisms of Messrs. Dowell and Foust's paper also hold in similar respects for Mr. Clem's discussion on the subject of calculated surge voltages.

### *3. The Sphere Gap.*

In his discussion Mr. Clem refers to studies made on the 50-cm sphere gap to determine polarity and time lag effects; he states that neither of these effects exists in appreciable amount within the range of surge voltages he has considered. Mr. Lloyd states rather bluntly that "the accuracy of sphere gap in sparking over without appreciable time lag on the crest of either the short or long wave cannot be questioned." Harding and Sprague caution the use of sphere gaps for rapid surge voltage measurements, and suggest means to pre-ionize the air between the gap and thus eliminate possible time lag effect. Furthermore, Messrs. Fielder and McAuley recommend that sphere gaps duly be calibrated for work in surge voltage measurements.

In the paper and in the writer's previous discussion investigations made on the 200-cm and on the 25-cm sphere gaps have been reported. Similarly, the 6.25-cm sphere gap has been calibrated with the resistance potentiometer; its calibration curve follows the A.I.E.E. curve up to approximately 3 cm gap separation but rises well above the A.I.E.E. curve for the wider separations.

Fig. 27 gives the 200-cm sphere gap calibration down to gap separations of several centimeters. It shows that a small difference exists between the surge voltage flashover for positive and negative waves, the positive wave value being less than the negative wave value.

Fig. 25c gives the flashover of the 200-cm sphere gap (aluminum spheres) when the gap is adjusted just to flashover. The gap separation is 30 cm. The full wave of the surge applied is shown in oscillogram Fig. 25B; to obtain this wave the internal resistance $R_s$ in the surge generator was reduced to a minimum, the other surge generator constants being $C_s = 0.024\ \mu f$ and $L_s = 30\ \mu h$. Two conclusions are derived from this oscillogram. First, the sphere gap missed the first crest of the oscillation and flashover took place at the second crest of the oscillation. Second, the resistance potentiometer was located approximately 20 circuit feet in front of the sphere gap, and it therefore recorded a voltage less than the sphere gap flashover voltage by an amount equal to the lead drop. Fig. 25c then shows that a time lag effect exists particularly in the case of certain waves which nevertheless are encountered at times in the laboratory. As pointed out in the paper the time lag effect may occur even in the case of a long, flat wave surge. Fig. 25c confirms emphatically that measurements must be made close adjacent to the test piece, particularly in the case of very fast surges and when all damping resistance is removed from the surge generator circuit.

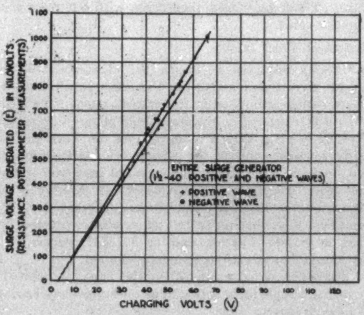

FIG. 24—RELATION BETWEEN CHARGING VOLTS ($V$) AND SURGE VOLTAGE ($E$) APPLIED TO TEST PIECE (TEST BETWEEN ELECTRODES IN OIL)

Referring to Fig. 25D, the internal resistance $R_s$ was increased to 200 ohms and a wave as shown in oscillograms Fig. 26A and B was recorded. The surge voltage was adjusted to a value appreciably above the sphere gap setting (18.75 cm). Flashover took place on the rising front; the voltage as computed from the A.I.E.E. standards is a few per cent within the resistance potentiometer measurement.

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[7] For discussion of results in another laboratory see also "Technique of Surge Testing," F. D. Fielder, *Electric Journal*, February 1933, p. 73.

Even for waves that are normally or are at times used in the laboratory, it is not justified to state that no time lag effect exists for sphere gaps. Neither can it be said that no polarity effect exists. When flashover takes place on rising fronts in a fraction of a microsecond, the time-lag effect then becomes more prominent.

It cannot be over-emphasized, that the characteristics and the limitations of sphere gaps as used in surge voltage measurements need to be set forth more clearly. Surely present A.I.E.E. calibration curves cannot be used indiscriminately as a standard for surge voltage measurement. Mr. Clem suggests that "the range (of the sphere gap) should be more limited than when used for 60-cycle measurements" and Mr. Peek states that sphere gaps be used up to separations not greater than one-half their diameter. These gentlemen then agree with our recommendations on this point.

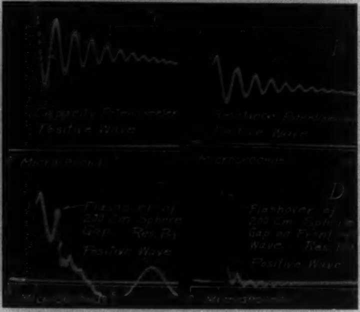

FIG. 25—OSCILLOGRAMS A, B, C AND D

*4. Resistance—Cable Divider.*

Mr. Bewley analyzes at length the characteristics of the cable-type divider and arrives at the same conclusions which either are stated or implied in the writer's paper. This coincidence is to be expected as the theoretical analysis presented by Mr. Bewley is essentially a reiteration of the work the writer originally covered; some of the generalized relationships in the original analysis were not found essential and were therefore omitted from the paper. Nevertheless Mr. Bewley is to be complimented for his analytical work. A great deal of the mathematical relationships he has given also is covered in the work of Heaviside, Carson, and in A.I.E.E. papers,[8] which Bewley himself has at various times contributed.

The derivation of equation (2) in the paper is pointed out briefly and in simple form herewith as questions may have been raised as to its source. Let

$E$ = rectangular surge voltage applied (Fig. 3 of the paper)
$R_0$ = resistance of potentiometer ($R_0$ may be in the order of a thousand times greater than either $Z$ or $R_T$)
$Z$ = surge impedance of cable
$L$ = length of cable
$v$ = velocity of propagation in cable
$R_T$ = terminal resistance

The initial current and voltage waves set up in the cable at time $t = 0$ are

$$i_0 = \frac{E}{R_0 + Z} = \frac{E}{R_0} \text{ (very nearly)}$$

$$e_0 = \frac{EZ}{R_0 + Z} = \frac{EZ}{R_0} \text{ (very nearly)}$$

The current and voltage at the terminal of the cable from time

$$t = \frac{L}{v} \text{ to}$$

$$t = \frac{3L}{v} \text{ are}$$

$$i_T' = \frac{e_T'}{R_T}$$

where
$$e_T' = \frac{2R_T}{R_T + Z} \cdot \frac{EZ}{R_0}$$

By successive reflections between the two ends of the cable that can readily be calculated, the terminal current and voltage approach very nearly the steady values

$$i_T = \frac{E}{R_0}$$

$$e_T = \frac{R_T}{R_0} E$$

The ratio between the terminal voltage upon the first reflection, *i.e.*, $e_T'$ and the subsequent steady value $e_T$ is then as stated in equation (2) of the paper.

The effect of terminal capacity $C_T$ due to the oscillograph plates, etc., obviously is negligible for wave fronts in the order of ½ microsecond and even less, as the time constant of the terminal impedance and the cable surge impedance only is a small fraction of the duration of the steepest front that would at the present be measured. We have covered the subject on the effect of distortion and attenuation at sufficient length. A few hundred feet of cable may be permissible, provided it has the desirable characteristics of practically no distortion, no attenuation, and a practically constant surge impedance.

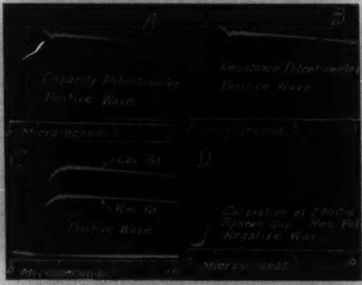

FIG. 26—OSCILLOGRAMS A, B, C AND D

It also is obvious that the inductance of the resistance potentiometer is of secondary importance and that only the distributed capacity need be considered.

Let for example

$R_0$ = 10,000 to 50,000 ohms
$C_g$ = 20 to 100 $\mu\mu f$
$L$ = 10 to 20 $\mu h$,

then obviously the time constant $\frac{R_0 C_g}{4}$ is much greater than

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[8] See for example: *Traveling-Wave Voltages in Cables*, by H. G. Brinton, F. H. Buller, and W. J. Rudge, TRANS. A.I.E.E., March 1933, p. 121-132.

$L/R_0$. Therefore from a practical standpoint there is no need to consider the inductance of the potentiometer in analyzing the circuit of Fig. 13 of the paper.

The writer's analysis of the characteristics of the resistance potentiometer points out the essential elements of the problem. There are many other practical considerations which invalidate any attempt at too rigorous and detailed analysis. From a practical standpoint we see no need to enter into greater details at the present.

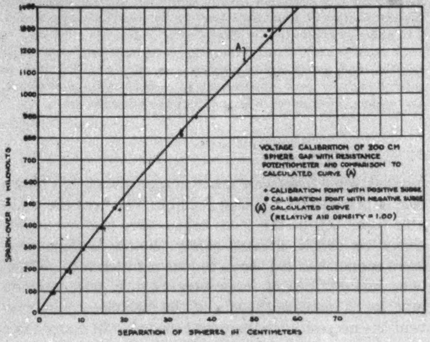

Fig. 27

Mr. Fielder raises the pertinent question as to the values of $R_0$ and $C_g$ which are representative. The values given in Figs. 14 and 15 of the paper are conservatively high but nevertheless representative. These curves can readily be extended to the lower values of $R_0$ and $C_g$ which frequently are found in practise.

Fig. 25A and B compares the response of the resistance potentiometer (approximately 10 ft in length and 10,000 ohms resistance) to that of the capacity potentiometer. The voltages in this case are not measured at exactly the same point in the surge generator discharge circuit, but with the same oscillation superimposed on the exponential component of the wave the pertinent fact is that the surge voltage should rise to crest value at the same time for both the resistance and the capacity potentiometers. This is demonstrated clearly by comparing the time required for the two waves to rise to crest value. Fig. 26A and B is another comparison between the same resistance and capacity potentiometer. Fig. 26C still is another comparison, in this case the wave is of longer duration and is smooth along the front. Mr. Clem should find the above oscillograms of interest as they show that it is possible to use the resistance cable divider as successfully for the short wave as for the long wave.

*5. Capacity Divider.*

Experience with the capacity potentiometer during the past year further substantiates the consistent and satisfactory results that had been obtained previously. The operation of the capacity potentiometer as arranged at the Sharon laboratory meets all practical requirements for the surge testing of transformers. It is gratifying to see that the capacity potentiometer lately has been adopted in other laboratories.[9] The oscillograms in Figs. 25 and 26 and in the paper speak favorably for the capacity potentiometer. Provided the requirements and precautions mentioned in the paper are followed, the objections raised by Mr. Foust and Mr. Lloyd are removed.

The writer prefers the explanation of the theory of the capacity potentiometer as it is given in the paper. The relationships developed in Fig. 16 take care automatically of varying capacity due to space charges, which Mr. Foust mentions. It may be added that the shields have not increased appreciably the capacity of the surge generator at Sharon. The capacity components of the capacity potentiometer in Fig. 18 of the paper are maintained constant by maintaining all metallic parts of the generator, such as static shields, sphere gap, etc., in a given position and also fixing the position of the pick-up elements and of the oscillograph plates.

The following table illustrates the consistent sensitivity of the capacity potentiometer. This particular potentiometer is an adaptation of the one described in the paper and is used to measure surge voltages in the low voltage range from 100 kv to 400 kv.

| | | Resistance potentiometer | | Auxiliary capacity potentiometer | |
|---|---|---|---|---|---|
| Oscillogram No. | Charging volts | Deflection inches | Voltage kv | Deflection inches | Kv per inch |
| A | 75 | 1.58 | †321 | 1.83 | 175 |
| B | 62 | 1.32 | †268 | 1.50 | 178 |
| C | 50 | 1.05 | †213 | 1.20 | 178 |
| D | 36 | 0.76 | †154 | 0.87 | 177 |
| D | 44 | 0.90 | *182 | | |
| E | 44 | | | 1.02 | 178 |

*Multiplier for resistance potentiometer

$$= \frac{10{,}250 + 43.36}{43.36} \times 0.850 = 202 \text{ kv per in.}$$

†Multiplier for resistance potentiometer

$$= \frac{10{,}290 + 43.36}{43.36} \times 0.850 = 203 \text{ kv per in.}$$

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[9] The *Electric Journal*, January 1933, p. 8.

# Circuit Breaker Protection for Industrial Circuits

BY H. J. LINGAL* and O. S. JENNINGS†

Non-member Associate, A.I.E.E.

***Synopsis.**—The demand for continuity of service to customers, together with the need to reduce maintenance costs, and increase the safety to operators and property, has made it necessary to improve the protective devices used in the distribution circuit. In the past, this protection has been provided by knife switches and fuses. Limited interrupting capacity of knife switches, together with the possibility of abuse of the fuse, has made it impossible to obtain these desirable characteristics.*

*Increase in design knowledge, the development of new materials, together with an increase in knowledge of arc phenomena, and of arc interrupters has made possible the construction of circuit breakers occupying small space. These same devices are capable of rendering performance superior to that given by older apparatus. At the same time, low cost to the user is obtained, together with safer and more satisfactory service. Safety construction of apparatus, together with tests of unusual severity, assure a product capable of providing a degree of protection to property and life which is considerably more than that obtained from knife switches and fuses, which in many cases can be tampered with and handled while the circuit is alive.*

*The new circuit breakers are suitable for very broad application in all varieties of distribution circuits within the scope of their rating. Standardization of dimensions provides for economical application. The scope of application of these devices is the field now filled by knife switches and fuses, together with many applications in which small oil and carbon circuit breakers are now used. This field in general includes such applications as switchboards, panelboards, load centers, meter entrance equipment, and enclosed switches.*

* * * * *

## HISTORICAL

PROTECTION of circuits from injury or destruction, with the attendant danger to life and property has received continuous attention from engineers and designers all through the history of the distribution of electrical energy for power and illuminating purposes. Protection was necessary in the circuits chiefly to guard against danger created by overloads or unusually heavy current rushes due to short circuits or grounds on the circuit. Of these, the more important was probably the overload, as short circuits, while likely of frequent occurrence, were of small power and could readily be handled by simple devices.

Protective devices then were of the most simple form. The sole object being to open the circuit, if necessary at the expense of destroying the protective device itself, and many times this was accomplished only after considerable damage to property.

The oldest protective device was a section of the circuit which melted when overloads occurred and disconnected the source of power from the point of trouble. Early devices of this type consisted of simple copper wires, or other conductors having a fusing value less than the circuit. These were connected between binding posts or terminals, in air. Evolution in the art finally produced the fuse, and the knife switch which was the only recognized protective device until recently.

Further development, and the necessity for better protection resulted in an enclosed fusible device in which the interrupting capacity was not greatly improved, but a greater safety to apparatus and adjacent property was obtained. Later the fuse cartridge was filled with suitable powders or other materials, still further improving performance.

As the demand for convenience, and protection increased, some fuses were made in such a way that blown elements could be replaced readily. This was the refillable fuse. All of the steps taken were improvements, either to obtain greater safety, better performance, more economical use, or to reduce maintenance. When open installations of fuses were used, it was common practise to increase the size of the fuse element to prevent the necessity for frequent renewals. In many cases circuits were badly overfused and all protection was lost. To obtain increased safety, fuses and suitable disconnecting switches were combined together in a common enclosure, access to which could only be obtained, in many cases, by capable and authorized operators. While safety was materially increased, the element of convenience was lacking.

## DEMAND CREATED FOR IMPROVED PROTECTION

The general speeding up of industry witnessed in the past two decades would not tolerate delay and inconvenience, and has demanded the replacement of any device not able to keep pace, or to meet the new demands made upon it. An open circuit must be reclosed without delay, as soon as the safety to men will permit. Carefully engineered circuit layouts planned to distribute energy at the minimum cost of both distribution and installation require protection that will assist them to perform in the fullest manner the functions for which they were designed. Processes which in their performance, demand continuity of supply, likewise make improved protective devices necessary.

The modern industrial circuit must have dependable protection which cannot readily be tampered with. Careful engineering is wasted and safety sacrificed if someone destroys the value of protection by substitution of protective parts of increased current capacity. The need for better circuit protection has been stressed for many years by fire underwriters and safety councils. Meanwhile the manufacturers of electrical devices have been working to provide better devices.

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

†Westinghouse Elec. & Mfg. Co., Mansfield, Ohio.

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### REQUIREMENTS

Satisfactory protection carried with it the requirements of:

1. Being able to provide time delay to permit starting of motors, and other operations requiring temporary overload for their performance.
2. Have sufficient interrupting capacity to handle any short circuit likely to occur on the circuit it is protecting.
3. Ability to remove instantaneously a short circuit from the line being protected.
4. Any satisfactory device must be capable of being operated repeatedly in a satisfactory manner, under any condition to which it may be normally subjected.
5. It should be capable of being operated any desired number of times at the will of the operator.
6. It must be built in such a manner that the operator will be safe while operating it.
7. Accessibility and convenience are necessary.
8. The device must not present a fire hazard in any respect.
9. Its performance under unusual duty should not be noisy; or disturbing to the operator or those near it.
10. It must be easy to apply, small in size, and low in cost.

The circuit breaker was the only device available, capable of meeting most of the requirements, but the cost of a breaker of suitable rating and the space required for its mounting prohibited, for many years, the adoption of the device.

### ACCOMPLISHMENTS

Several years ago a small circuit breaker was built, the size of which had been reduced so that in use it occupied about the same space as a switch and fuse of comparable rating. In this circuit breaker there was incorporated a modification of the deion arc interrupter. This breaker had the ability to perform every required function necessary for circuit protection. The first breaker was built in only the 15 amperes 125 volt size and had an interrupting rating of 5,000 amperes. See Fig. 1. Additional ratings have since been developed until now a line is available up to 600 volts and 600 amperes as illustrated in Fig. 2.

Circuit breakers of the conventional type commonly in use extinguished the arc by drawing it to such a length as to cause it to become unstable. Such breakers were not suitable for the protection of branch circuits, because of the space required for their installation. Before a satisfactory circuit protective device could be produced, it was necessary to obtain an interrupting means which would greatly reduce the size of circuit breakers. Dr. Slepian used the theory of deionization to explain circuit interruption,* and suggested a mechanical design of a circuit interrupter which could be adapted to circuit breakers of the type which interrupt the circuit in air. O. S. Jennings at the same time was developing the slotted plate extinguisher, for safety switches, which he applied to these circuit breakers with perfect success. By the aid of the principles which Dr. Slepian had proposed, these extinguishers were finally improved to provide safe interruption at voltages up to 600 volts. The interrupter shown on the breaker in Fig. 4 was the first form used on the Jennings switch referred to. This interrupter requires two plates for each 125 volts of line voltage to be opened. For example, one suitable for opening 250 volts would require 4 plates. As the voltage increases, two plates are added for each 125 volt increase. This interrupter consists of the arc drawing contacts shown at (*B*) in the same figure and the quencher of two or more steel plates (*O*). Upon parting the contacts (*B*), the arc drawn is acted upon by two forces, first, the dense magnetic field produced in the angle created by the contacts and the arc tends to push it off of the contacts and into the slotted portion of the plates. In the slotted portion of the plates a magnetic field about the arc and through the plates exerts a force which pulls the arc to the magnetic center of the plates, at which point it stops moving until, at the end of the next current zero, when current has ceased to flow, the rapid deionization of a cathode layer on the plate surfaces prevents restriking of the arc, and the circuit is interrupted.

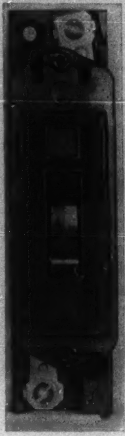

FIG. 1—15-AMP, 125-VOLT, SINGLE POLE CIRCUIT BREAKER

For the higher voltages, and higher interrupting capacities, more effective interrupting is obtained by the use of a deionizing quencher in which the long arc is divided into a number of short arcs, and is made to travel continuously in an annular path instead of stopping as described in the case of the quencher for lower voltage breakers.

The interrupter for higher voltage breakers is illustrated in Fig. 3, and is constructed in the following manner:

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*Extinction of an A-C Arc*, by J. Slepian, A.I.E.E. TRANS., Vol. 47, 1928, p. 1398.

An extended portion of the main stationary contact is used, upon which to build the quencher, which is constructed in the following manner. An arcing contact member designed to receive one terminal of the arc, and so shaped that the current in passing through it produces a flux in the correct direction to increase the strength of the magnetic field, which drives the arc to the narrow end of the tapered entrance to the plates, is mounted on the main contact member and insulated from it. Upon this member and insulated from it, and from each other, are mounted four copper plates, each of which is set into a steel plate. Next, a five turn coil, the terminals of which are fastened to two plates, one of which is assembled on either side of the coil and insulated from the plates adjacent to it and from the turns of the coil. On the top of the coil assembly there is assembled three more combination plates, and a cover plate. Between each plate and the one next to it an annular raceway is formed by the plates and insulating members. The top plate of the whole assembly referred to as the cover plate, is electrically connected to the moving contact through a shunting member. A hollow steel stud solidly connected to the extended portion of the main stationary contact projects through, and is insulated from the plates and coil. This serves the triple purpose of holding the entire assembly together; providing a portion of the magnetic circuit for the coil which produces the flux which drives the arc on the annular portion of the plates. Being hollow, it also provides for the passage of a screw which is used to secure the quencher to the breaker frame, and at the same time acts as a portion of the conductor to carry the current during the period of arcing from the arcing tip back to the breaker terminal. The circular raceway on the copper plates is obtained by cutting out the center of the insulating material, used between the plates, to the size and shape of the raceway desired, thus permitting the arc to extend from plate to plate. Copper is used in the plates on which the arc is carried, because an arc will move freely over the surface of a copper plate, whereas, it lags, or refuses to move on most other materials. The action of the magnetic field set up by the arc in conjunction with the roughly U-shaped steel plates is used to move the arc from the contacts into the quencher, and on to the copper plates, where it is broken into a number of short arcs. At this point the arc comes under the influence of a magnetic field produced by the coil, which is located in the center of the plate structure.

FIG. 2—600-AMP, 600-VOLT, 3 POLE CIRCUIT BREAKER

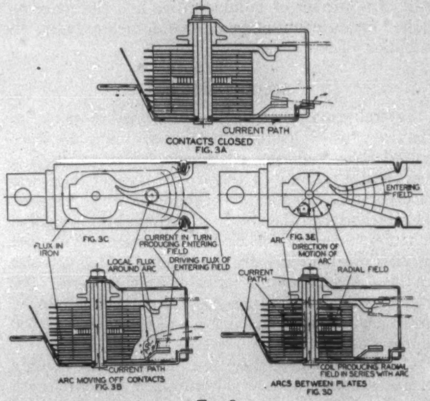


FIG. 3

*A* Interrupter—showing path of current—breaker closed
*B* Interrupter—showing path of current as contacts part
*C* Interrupter—showing flux fields produced by the current in the arc, and conductors, as the contacts part
*D* Interrupter—showing path of current, and flux field when arcs have been transferred to deion plates
*E* Interrupter—showing flux field causing arc to move on plates

Actuated by this field, the arc is caused to travel about the annular path at a high speed (1,100 ft or more per second).

Referring to Fig. 3A, the breaker contacts are shown in the closed position, and the path of the current is then through the extended portion of the main stationary contact, and the contacts themselves as shown by the arrows. In Fig. 3B, the contacts are shown open with an arc drawn between them. The path through which the current flows is now, from the terminal end of the stationary part of the main contact, to the stud in the center of the stack, then through an extension of the arcing tip member, the arcing tip, then through the arc to the moving contact member. Fig. 3B illustrates the flux field produced by the current during a moment when the current is flowing through the portion of the circuit and the arc is shown at Fig. 3A. The local flux around the arc, the flux in the iron plates, and the flux from the current in the turn producing the entering field, all combine to force the arc to travel at high speed to the end of the tapered entrance where it ceases to exist as one long arc, by being broken into a number of short arcs as shown in Fig. 3D. At this time the coil which produces the radial field is inserted into the circuit in series with the short arcs. The flux field produced by the radial field coil is shown in Figs 3D and 3E. This flux acting with the flux in the field produced by the short arcs, will cause the arcs to move in the direction shown in Fig. 3E, thus producing the motion and speed necessary to prevent formation of molten spots or hot cathodes on the copper plates. If the time selected for consideration of the current path, and fields produced, should have been one-half cycle earlier, or later, the direction in which the current is shown to be traveling would be reversed. Likewise, the direction of the flux in all the separate fields would have been opposite to the direction shown. This change in the direction of the current, and the flux fields, would still produce the same direction of motion in the arc, as can be observed by reversing the direction of all the arrows in the illustrations Figs. 3B-3C.

The arc having been broken into a number of short arcs, and caused to move by the means just described, continues to travel in the annular path until a current zero is reached. At this time, if the contacts have separated a sufficient distance to prevent restriking, the arc will be extinguished. In case sufficient separation may not have been obtained between the contacts to prevent restriking through the air, the process of drawing the arc to the end of the tapered entrance, breaking it into short arcs, and moving it around the annular path would be repeated, until the contacts have opened a sufficient distance to prevent restriking.

The selection of materials for contacts was difficult because there had not been sufficient demand to warrant their development up to this time. After much research and testing, it was found that certain mixtures of graphite and silver made a contact member suitable for the lower current breakers as this contact had a low resistance, resisted arcing, and would not weld. This material was suitable for use on breakers normally rated 100 amperes or less. Difficulty was encountered in its use on breakers rated 200 amperes or more, which made it necessary to continue research work still further. The result was the selection of silver and tungsten combinations for breakers rated normally at more than 100 amperes. A further division was necessary because the arcing could not be taken on the main current carrying contacts of the higher current breakers, which made it necessary to separate the arcing portion of the contact from that portion which is intended to carry the normal load. Here again it was necessary to select different materials for the arcing contacts and main contacts. The main contacts required a material having resistance to welding, and low contact resistance at all times. Silver was the best material available, but was unsuitable because of its tendency to weld when carrying heavy current. To overcome this fault, a combination was developed in which the material was silver mixed with tungsten, molded under heat and pressure.

For the arcing contact parts another combination of the same materials was used in which the percentages of the different materials was changed to increase the tungsten and decrease the silver content, which, while it lowered the ability of the contact to carry current continuously, greatly increased its capacity to withstand the destructive action of the arc.

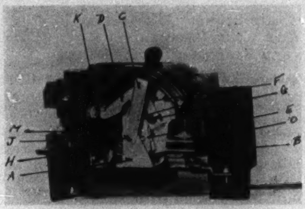


FIG. 4—SECTION THROUGH 15-AMP, 125-VOLT BREAKER SHOWING DETAILS OF CONTACTS AND MECHANISMS*

| | | | |
|---|---|---|---|
| *A* | Frame | *G* | Fulcrum for latching cradle |
| *B* | Contact bar | *H* | Fulcrum for contact bar |
| *C* | Operating handle | *J* | Fulcrum for operating handle |
| *D* | Latching cradle | *K* | Latch |
| *E* | Toggle linkage | *M* | Bi-metal |
| *F* | Operating springs | | |

Operating mechanisms commonly used for operating breakers did not possess all of the requirements needed, and a new design was brought out which was trip-free of the closing handle in all positions when the trip mechanism was actuated. It also was quick-make and quick-break, and held the contacts in the closed position by means of an over-center toggle, which is broken by changing the position of the fulcrum point on the latching cradle when the trip latch is released. The mechanisms used on all breakers are built to incorporate the same general principles although it is necessary to make structural changes in size and shape of the parts to make them suitable for the different sizes of breakers on which they are used. Fig. 4 shows a 15-ampere breaker in which the case has been cut away, to permit a view of the mechanism which, while of the smallest size, is typical of the mechanisms for the entire line. The mechanism is assembled from and consists of the parts as shown in the illustration.

The frame member (*A*) is designed to provide the necessary bearings and fulcrums essential to the operation of the mechanism. On this member is fulcrumed at (*H*) the contact bar (*B*). The contact bar is operated through its travel by means of the toggle links (*E*) which are fulcrumed at one end on the contact bar and on the other end to the latching cradle (*D*). The latching cradle (*D*) is fulcrumed on the frame at (*G*) and latched on the bi-metal at (*K*). Operating springs (*F*) have one end secured to the hinge pin of toggle links (*e*) and the other end to the operating handle (*C*). Assuming the breaker to be in the open position and the latch at (*K*) disengaged, the operations to reclose the breaker are as follows:

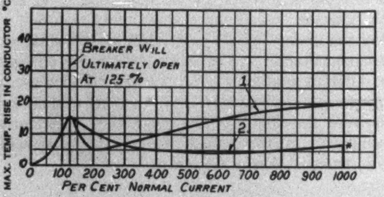


FIG. 5—CURVE SHOWING TEMPERATURE RISE ON RUBBER-COVERED WIRE WHEN CARRYING ITS RATED CURRENT, AND PROTECTED BY A BREAKER OF PROPER RATING

1. No. 14 rubber-covered wire protected by a 15-ampere *AB* deion circuit breaker
2. 220,000-cir mil, rubber-covered cable protected by a 225-ampere *AB* deion circuit breaker

* At 1,000 per cent and above, the 225-ampere breaker trips instantaneously

The operating handle is moved toward the bi-metal forcing the end of the latching cradle into engagement with the latch member on the bi-metal at (*K*). The mechanism is then in the reset position and ready to reclose the breaker. Pushing the operating handle (*C*) toward the contact end of the breaker increases the tension on the springs (*F*) and when movement continues further the direction of the pull on the toggle links is moved from one side of the center line of the upper link to the other side of the same center line. The pull of the springs then cause the toggle linkage to move to the opposite side of the center line of the on toggle position. In doing so, the contact bar is moved at high speed from the open to the closed position and locked against opening by means of the over-center toggle. To open the breaker manually the operating handle is pulled downward, toward the latch, and until the direction of pull of the operating springs, one end of which is moving with the handle, has been transferred to the opposite side of the toggle center when the springs being under considerable tension pull the toggle over center in the direction to open the contacts. Since the springs are under full tension at this time, the movement of the toggle linkage and the contacts will be very rapid. In opening automatically, the latched end of the latching cradle (*D*) is released at (*K*) by the movement of the bi-metal (*M*) which on the breaker shown carries all the current passing through the breaker and is caused to deflect away, from the latching cradle, by the heat generated in it. The latching cradle upon being released moves upward and shifts the upper fulcrum point of the toggle linkage to a point on the opposite side of the line of pull of the operating springs, whereupon the toggle is free to move to the collapsed position carrying with it the contact bar to the full open position.

The complete line of breakers are tripped automatically on overloads by means of bi-metal tripping elements which provide inverse time delay tripping because of their thermal characteristics. The bi-metals used on breakers rated normally at 100 amperes or less are heated directly by the passage of current through them. Bi-metals on breakers rated more than 100 amperes do not carry the current, but are heated indirectly by means of heaters, which are in series with and form a part of the conductor through the breaker. Breakers rated 70 amperes or more are also provided with a solenoid trip operated by a one-turn series coil. These trips are normally set to function at about ten times the normal rating of the trip element, and having no time delay enable the breakers to clear a line in case of a short circuit in a very short time.

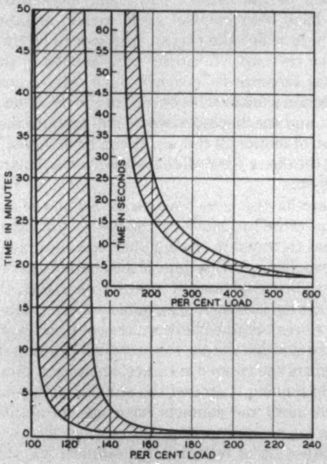


FIG. 6—BAND CURVE, 15-AMP TO 25-AMP BREAKER

Breakers rated at less than 70 amperes do not have the instantaneous trip. In such cases the series bi-metal is heated directly by the passage of current through it and consequently reaches a temperature which will produce sufficient deflection to cause tripping in less than one-eighth of a cycle of 60-cycle current at interrupting rating.

Tripping elements are built integral with, and calibrated in the breakers for rating less than 70 amperes, but for breakers of larger current rating they are built as a unit, calibrated, and sealed, and are interchangeable. Likewise, it is possible to equip any breaker normally rated 70 amperes or more with trips having a normal current rating of 50 amperes or more up to the rating of the breaker. In order to meet requirements of the underwriters, all tripping elements are sealed to prevent tampering or changing of their calibration by unauthorized persons.

The bi-metals are designed with a time current curve that always will protect the conductors of a circuit on which they are used, if correctly applied.

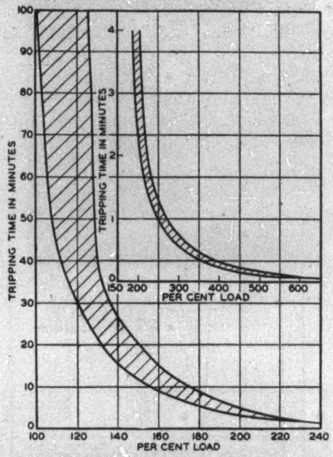


FIG. 7—BAND CURVE, 225-AMP BREAKER

The curve shown in Fig. 5 shows the temperature rise in No. 14 rubber covered wire when protected by a 15-ampere deion circuit breaker and a 200,000-cir mil cable protected by a 225-ampere breaker. At 125 per cent load the wire temperature rises about 16 deg C and the breaker opens ultimately, while at 30 amperes the rise is but 5 deg C and the opening time is 20 seconds. At 150 amperes the temperature rise is 20 deg C and the opening time of the breaker is one second, for the 15-ampere breaker. The curve for the 200,000-cir mil cable shows slightly different characteristics, as the temperature at the higher current is less than for the smaller wire.

Figs. 6 and 7 show characteristic band curves illustrating the performance of breakers rated from 15 amperes to 225 amperes inclusive.

The Underwriters' Laboratories requirements under which the type "AB" circuit breakers are listed, are as follows:

1. *Non-tamperable.*
2. *Trip free of handle.*
3. Unless rated alternating current, only, all tests to be made on direct current.
4. *Overload test.*
   50 operations at 150 per cent load.
   15 operations at 1,000 per cent load.
5. *Endurance test.*
   6,000 operations at 100 per cent load.
   Not over 6 operations per minute.
6. *Calibration test at 24 deg cent*
   0—30-ampere ratings must trip in 1 minute at 200 per cent load.
   31—60-ampere ratings must trip in 2 minutes at 200 per cent load.
   61—100-ampere ratings must trip in 4 minutes at 200 per cent load.
   101—225-ampere ratings must trip in 8 minutes at 200 per cent load.
   226—400-ampere ratings must trip in 15 minutes at 200 per cent load.
   401—600-ampere ratings must trip in 20 minutes at 200 per cent load.
7. Ultimate trip 125 per cent load.
8. Carry continuously 100 per cent load.
9. *Temperature test.*
   Current carrying parts, except thermal elements, must not exceed 30 deg cent rise when carrying rated current at rated frequency. The thermal elements of breakers rated at 225 amperes and above are replaced with copper bars when this test is made, as in the case of safety switches.
10. *Short-circuit tests.*
    A d-c rated circuit breaker must be short-circuited three times at two-minute intervals at rated voltage on a circuit set to give a line drop equal to 2 per cent of the rated voltage with rated current flowing, except the short-circuit current must not be less than 5,000 amperes and not more than 10,000 amperes.
    An a-c rated circuit breaker must be short-circuited seven times at two-minute intervals at rated voltage and rated frequency (60 cycles if none is specified) and 40 to 50 per cent power factor on a circuit set as above for d-c breaker. One three-phase short circuit and six single-phase short circuits are made all at not less than two-minute intervals. Of the single-phase short circuits, two are made on each pole, one *OCO* and one *CO*. The circuit is set as above for the three-phase short circuit and this same circuit is used for single-phase short circuit.
11. Check breaker tripping at 200 per cent load.
12. *Insulation test.*
    1,000 volts plus twice rated voltage between live parts and ground—opposite polarities—line and load contacts with breaker open.

Oscillogram A illustrates the performance of a 225-ampere breaker opening 10,000 amperes at 580 volts alternating current, 60 cycles, 40 per cent power factor.

The diagram in Fig. 8 serves to illustrate typical locations where breakers are suitable for use. At the extreme lower left the service enters a building. Beyond this point the main feeder is protected by a breaker at the service. From this main are taken various feeders. The first on the left is one for elevators, the motors for which may be located, for example, in a penthouse at the top of the building. The circuit for each elevator is in turn protected by a breaker.

Next is a feeder for a power panel, located on one of the upper floors. The next circuit shown is a lighting feeder which would serve the lighting panelboards for the building, or a section of the building. The last is a power feeder from which has been tapped a sub-feeder protected by a circuit breaker. From this sub-feeder are taken the various motor circuits.

The breakers shown at the main might be individual breakers in boxes, in the form of a switchboard, or in panelboard form, depending on the number of circuits and the nature of the building. The grouping of motor circuits might be accomplished in any one of these ways. Since the breaker mechanisms are all identical, the same performance would be obtained no matter what form the housing takes. Fig. 9 has been selected to illustrate some applications of the breakers to motor circuits. In this illustration, circuit No. 5 is one frequently found in practise. Immediately ahead of the motor is a motor starter with overload protection. The function of the starter is to operate the motor and protect its coils. Normally the protection afforded by the starter would protect the motor from excessive overloads whose value does not rise above the locked rotor current.

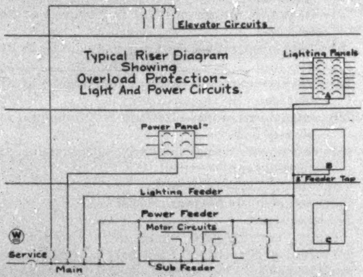
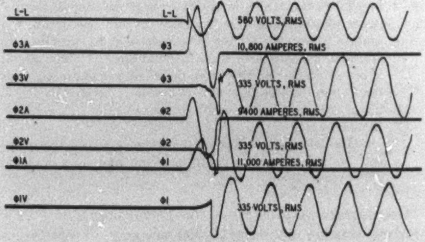

Elevator Circuits
Typical Riser Diagram Showing Overload Protection- Light And Power Circuits.
Lighting Panels
A
Power Panel
B
Feeder Tap
Lighting Feeder
Power Feeder
Motor Circuits
C
W
Service
Main
Sub Feeder

Fig. 8—Typical Riser Diagram of a Tapped Feeder Wiring System



Oscillogram A

The overcurrent device in the starter is designed to act with greater time lag than the circuit breaker, but in securing this lag the ability of the starter to interrupt current is reduced to approximately the locked rotor current of the motor. In the illustration, a breaker is placed immediately ahead of the starter. The function of the breaker in this case is to disconnect the starter and motor from the line, and to protect the starter, and motor from currents greater than the capacity of the starter to interrupt. In order that the time lag in the breaker will be sufficient to permit the starter to function on overloads within its rating, the trip element in the breaker is selected so that it will operate faster than the starter at about locked rotor current. It is obvious from the position of the starter, that it cannot give protection to anything but the motor itself, while the circuit breaker located at the source of the circuit affords protection for the entire circuit, starter, and motor.

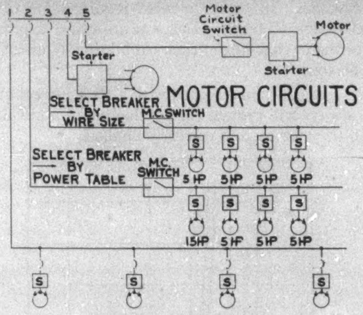

1 2 3 4 5
Motor Circuit Switch
Motor
Starter
Starter
MOTOR CIRCUITS
SELECT BREAKER BY WIRE SIZE
M.C. SWITCH
S
SELECT BREAKER BY POWER TABLE
M.C. SWITCH
5 HP
5 HP
5 HP
5 HP
15 HP
5 HP
5 HP
5 HP

Fig. 9—Motor Circuits

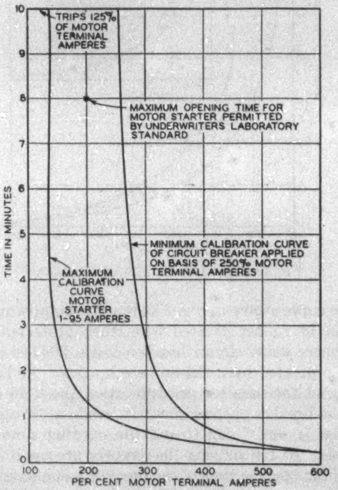


Fig. 10—Comparison of Motor Starter Curve and Circuit Breaker Curve

Circuit No. 4 shows the motor very close to the circuit breaker. In this case the switching function of the breaker may be utilized to omit the motor circuit switch. Circuit No. 3 shows a group of motors of the same size. If desired, one motor circuit switch may serve to disconnect all the motors. Circuit No. 2 is essentially the same type except that one motor has the capacity of more than 40 per cent of the total. Circuit No. 1 serves to illustrate a circuit in which it is not desirable to depend on the breaker at the origin of the feeder for protection, because a short circuit at any one of the motors would interrupt the operation of the others; for this reason a circuit breaker is placed on each separate motor circuit, even though conditions do not require such protection from a safety standpoint. If these are short taps, the motor circuit switch may be omitted.

FIG. 11—PANELBOARD COMPLETE

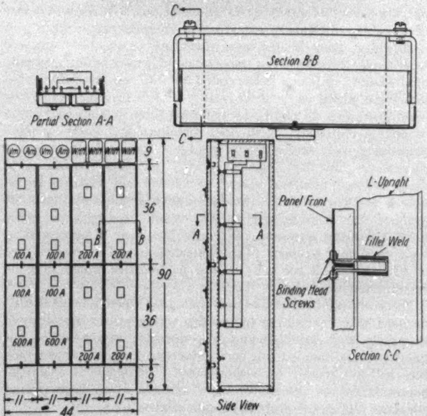

C
Section B-B
Partial Section A-A
C
Vm
Am
Vm
Am
Whm
Whm
Whm
Whm
9
36
B
B
100A
100A
200A
200A
90
100A
100A
36
600A
600A
200A
200A
9
11
11
11
11
44
Front View
A
A
Side View
L-Upright
Panel Front
Fillet Weld
Binding Head Screws
Section C-C

FIG. 12—ONE FORM OF DISTRIBUTION SWITCHBOARD ACCESSIBLE FROM THE FRONT FOR INSPECTION

At the present stage of development, the circuit breakers do not serve all of the purposes of a motor starter, and it is essential in many cases to use both the breaker and starter. In some cases, however, the breakers will perform all of the functions required, giving the required protection to both the motor and circuit.

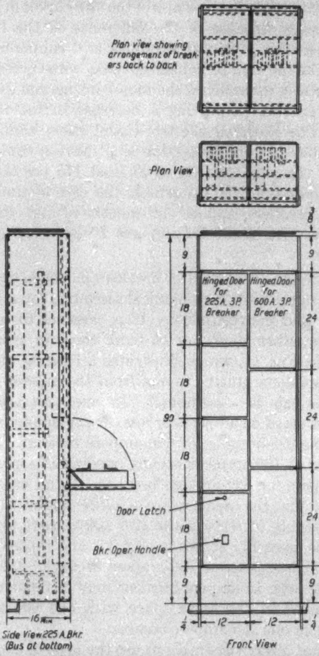

Plan view showing arrangement of breakers back to back
Plan View
3/8
9
9
Hinged Door for 225A. 3P. Breaker
Hinged Door for 600A. 3P. Breaker
18
24
18
90
24
18
Door Latch
24
18
Bkr. Oper. Handle
9
9
16 Min
1/4
12
12
1/4
Side View 225 A. Bkr. (Bus at bottom)
Front View

FIG. 13—A METHOD OF MOUNTING WHICH EFFECTS A HIGH DEGREE OF SAFETY

The curves in Fig. 10 show the difference in shape between a typical motor starter and a typical *AB* deion circuit breaker. The motor starter curve is plotted to show a tripping at 125 per cent of terminal ampere rating of a motor. The circuit breaker is plotted to carry 250 per cent of the motor full-load current. It is to be noted that the curves of the breaker and the starter cross about locked rotor current. As just described, due to the conditions surrounding a motor circuit, it is not desirable to have the circuit breaker trip below the pull-out load of the motor.

The small circle between the two curves represents the point established by the Underwriters' Laboratories as the maximum permissible time at which a motor starter shall trip at 200 per cent load,* which is, as previously stated, under the Underwriters' Laboratories standard for circuit breakers.†

If the circuit breaker curve were plotted to start at a lower ratio to the motor starter, it would cross the motor starter curve at correspondingly lower overload. If this ratio were still further reduced, it would be possible to reach a condition where, in ordinary plant operation, the breaker would trip before the starter.

The difference in the shape of the two curves in Fig. 10 is necessary because of the difference in the heating characteristics of motor windings and rubber-covered wire. As the size of rubber-covered wire increases, it more closely approaches the motor in thermal overload characteristics, permitting a decrease in the ratio of sizes. The National Electric Code‡ states that motor circuit overcurrent protection shall have a continuous current carrying capacity of at least 115 per cent and never more than 250 per cent in the case of time limit circuit breakers applied to motors of not over 30 amperes. At about 30 amperes 20 per cent only is allowed.

The design of all sizes of breakers has been carefully worked out to permit economical assembly, interchangeability, and convertibility. It is possible to use the breakers either singly, or to bank them in groups as shown in Fig. 11, which illustrates a lighting panel in which breakers ranging in size from 15 amperes to 600 amperes can be assembled. In such an assembly breakers rated 50 amperes or less occupy one-fourth the space of a 225-ampere, or 600-ampere breaker. Breakers rated at 100 amperes occupy one-half the space of a 225-ampere, or 600-ampere breaker. In all cases it is assumed that the breakers are of a like number of poles. It is possible to remove the two 100-ampere breakers from the assembly shown in Fig. 11, and replace them with a 225-ampere, or 600-ampere breaker. Likewise, 12-single pole, 15-ampere breakers may be removed and be replaced in the same space with one 600-ampere breaker, or one 225-ampere breaker.

It is not always desirable to use the type of construction shown in Fig. 11. The breakers are suitable for many other types of installation, and Fig. 12 illustrates a representative form of distribution switchboard accessible from the front for inspection.

Another form of construction adaptable to the economic grouping of breakers for power panels or switchboards is shown in Fig. 13. This method is more expensive than the method referred to in the previous paragraph, but provides greater accessibility, and at the same time enables the circuit breaker to be completely disconnected from the bus.

## Discussion

**R. E. Hellmund:** The desirability of replacing fuses and knife switches by suitable breakers has been pointed out in the paper and it is so obvious that it may cause wonder why it has not been done long ago. However, a study of the paper reveals that a great many engineering and research problems had to be solved before a suitable device was even possible. It is not obviously an easy problem to condense into a few cubic inches, an operating mechanism having quick make and break features for automatic or hand operation, trip free of the handle, a tripping mechanism with thermal features, contacts, and arcing space, all sufficiently large to handle 5,000 to 10,000 amp. Besides working out the structural design features, it required research and development on new arc rupturing methods and principles, new contact materials, new materials for the thermal elements, etc. These factors which are mentioned in the paper represent however, only a part of the problem. The testing with large rupturing currents in line with the underwriters' laboratories requirements, which for obviously practical reasons are and must be limited in number, had to be supplemented by numerous other tests. These included tests to determine the adequacy of the breakers on both direct current and alternating current, with various combinations of circuit constants such as resistance and inductance; with variations in damping effects in the circuit devices; with different locations of the impedances ahead or behind the breakers; with different grounding conditions and with different values of many other variables. It is true enough that the same variations were in the past encountered with fuse protection but the fuse had the advantage of gradual development and accumulation of experience with the growth of the electrical industry as a whole, while these breakers must at once meet the varied requirements of a fully established industry. Also as compared with a single operation of a fuse, many repeated operations, with a maintenance of operable conditions, are required of the breakers.

However, there is one more rupturing problem encountered with circuit breakers, the importance of which is not generally appreciated. A fuse is never called upon to rupture currents below those which cause it to melt. With a breaker permitting hand operation, an ability for handling these smaller currents is of course required. With open breakers and knife switches permitting wide separation of contacts these smaller currents present no difficulty. However, with the space limitations of these inclosed breakers, special provisions and features are required to take care of them and under certain conditions the problem fully is as difficult as that encountered with the maximum rupturing currents. Literally hundreds of thousand of tests were made to check all these conditions and assure coverage of probably 99.9 per cent of the possibilities which may be encountered in practise.

Even with all this, cases can be imagined where a breaker may be used with one of the higher d-c voltages in a circuit with extremely high inductance and no damping effects in the apparatus to be handled (air core inductance) where current rupture will not readily be accomplished. Of course it would be uneconomical to design for such extreme cases representing perhaps 1/100 per cent of the possible applications.

The number of tests and checks which were necessary with regard to the thermal trip elements were of the same order as those in connection with rupturing ability. Besides the features mentioned in the paper the ambient air temperatures had to be studied in combination with the influence of conductors, current carrying joints, other breakers and many other heat generating parts which may be mounted in close proximity to a breaker.

These are but a few of many additional items which add to the extreme complexity of a design problem which on the surface may look comparatively simple.

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*Refer to Underwriters' Test Procedure E-7819.

†Time established for 200 per cent of circuit breaker rating is 1 min for breakers up to 30 amp, 2 min for 60 amp, 4 min for 100 amp, and 8 min for 200 amp.

‡Page 119, Article 8, Sec. 808, Sub-C, and page 131, Article 8, Sec. 808, Table 6.

# Variable-Voltage Oil Well Drilling Equipment

## Comparison of Characteristics of Various Combinations of Motors and Generators

BY A. H. ALBRECHT*

Member, A.I.E.E.

***Synopsis.**—In the past, there have been many operating data taken and used in the comparison of the characteristics of various types of prime movers. However, there has never been a method established for the comparison of these equipments on a common basis. In this paper, such a method has been proposed. Although it deals only with internal combustion engine direct-current electric drives, with varying electrical characteristics, this method may be advantageously used for the comparison of other types of prime movers.*

VARIABLE-voltage direct-current drives are the most recent advance in electric oil well drilling equipment and have been successfully used by both the cable tool and the rotary method of drilling.

In the case of cable tool drilling, which consists of merely raising and dropping a heavy bit by means of a walking beam, the characteristics of d-c equipment result in improved motion of the drilling tool and in reduction of the time required for withdrawing the tools from the hole.

Rotary drilling, with its greater power requirements and greater complexity of operations, shows a more marked improvement when performed with d-c equipment than does cable tool drilling.

There are two fundamental operations when drilling by the rotary method, namely, the drilling operation and the hoisting operation. When drilling, hole is made by the downward pressure and cutting action of a revolving steel bit. The bit is rotated by means of a long steel pipe, extending from the drilling tool upward to a power driven rotary table mounted over the mouth of the well. Although the table has a positive grip on the drill stem, the latter is free to move vertically through the table while it is in motion.

To the top of the drill stem a swivel is attached, which provides a means of suspending the stem in the well, allowing it to rotate with the table, while the upper part of the swivel, the hoisting block and supporting cable, remain stationary. The drill stem and swivel are hollow so that mud can be pumped down the drill pipe to the drilling bit and out into the well through suitable holes in the bit. This fluid picks up the material loosened by the bit and carries it to the surface through the space between the drill pipe and the walls of the well. This circulation of fluid through the well is maintained by the pressure of two pumps connecting through a flexible hose to the swivel on top of the drill stem.

The swivel, drill stem, and bit may be raised or lowered in the well by means of a steel cable, operating through a hoisting block strung from the sheaves at the crown of the derrick. The free end of this cable passes down the derrick and is wound on a hoisting drum. This drum is a part of the drawworks which serves as a distribution center for all power-driven parts of the rig except the pumps. A system of chains, sprockets, and clutches is so arranged that normally, four-speed ratios may be obtained at the drum.

In order to replace a dulled bit, the entire drill stem must be withdrawn from the hole and is accomplished by removing the drill pipe in approximately 90-foot sections. During this operation, the hoist motor is loaded to its maximum capacity, for it is customary to hoist the drill stem at the greatest practical speed.

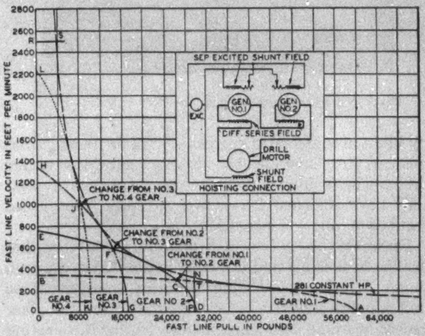

FIG. 1—COMBINATION 1

When returning the drill stem into the well, it is necessary to raise the empty elevators as rapidly as practical.

For performing the complete hoisting cycle in the most satisfactory manner, it is necessary that the hoisting motor be capable of exerting high torque for short periods of time, have a high no-load speed, and be capable of being reversed quickly.

The pumps used for circulating the mud are called upon to operate over a wide range of pressure and volume. In case the bit becomes plugged, it is desirable that the pump stalls at a safe working pressure.

In order to perform all of the pump operations satisfactorily, it is essential for the mud pump motor to have

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*Standard Oil Co. of California, La Habra, California.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

a high no-load speed, a definite limit of maximum torque and, because of the continuity of operation, to operate efficiently at all speeds.

A typical installation of a variable-voltage drilling equipment consists of a power plant (see Fig. 5) located at a safe distance from the drilling rig, and two motors located in the drilling rig.

The power plant consists of two d-c generators with direct-connected exciters. These generators may be driven by an a-c electric motor, taking energy from the usual power supply, or they may be driven by steam or by internal combustion engines. All of the installations made to date have used the internal combustion engine drive. The requirements for the prime movers are that they have sufficient horsepower capacity, good speed regulation, and low operating costs.

Birdseye View of Derrick and Generating Plant

One motor drives the drawworks and is used for either drilling or hoisting and the other motor drives the mud pump. During the drilling operation, one generating unit supplies power to the drilling motor and the other generator to the mud pump motor. During the hoisting operation, however, as the mud pump is not ordinarily used, the power from both generators is supplied to the drilling motor.

In view of the different operating characteristics obtainable by the use of various types of motor and generator windings, and interconnections between machines, an investigation was carried on to determine which combination was best suited for rotary drilling. This study included the following combinations:

1. Differential generators designed for series connection, supplying energy to a shunt drilling motor.
2. Differential generators designed for parallel connection, supplying energy to a shunt drilling motor.
3. Differential generators, designed for series connection, supplying energy to a compound drilling motor.
4. Shunt generators, designed for series connection, supplying energy to a compound drilling motor.

Each of these combinations uses the variable-voltage system of control. When the two generators are connected in series, to supply full power to the drilling motor for hoisting, the drilling motor is operated on double voltage, thereby doubling the motor speed and horse power. However, neither the motor ampere input nor the available motor torque is changed.

When the two generators are connected in parallel to supply the total power to the drilling motor, the voltage applied to the drilling motor remains the same as when one generator is connected to it. However, the available current is approximately doubled, thereby doubling the horse power output of the drilling motor.

Combinations 1, 3 and 4, as listed above, use the series connection of generators and combination 2 uses the parallel connection of supplying maximum power to the drilling motor during hoisting.

## Points of Consideration

In order to make a complete study of the series and parallel connections under discussion, the following points are considered:

1. Suitability of operation.
2. Relative first cost and operating charges.
3. Relative installation costs.
4. Relative safety.
5. Choice of size of equipment.
6. Choice of electrical characteristics.

A View of the Generating House

Showing internal combustion engines, direct-current generators and exciters

Since this is a comparison of electrical equipment and schemes of arranging electrical equipment, the drawworks efficiencies are considered to be one hundred per cent. The excitation is considered constant in all combinations.

*1. Suitability of Operation.*

*Parallel Connection.* It is necessary to use differential compound generators for parallel operation in oil well service. These generators have two fields; namely, a separately excited shunt field, and a differential self-excited field. The differential series field opposes the shunt field, thereby causing the generator voltage and consequent motor speed to droop with increase of load. This characteristic permits adjustment of the generator output to a value such that the prime mover cannot be stalled during normal engine operation, consequently preventing the overloading of the prime mover.

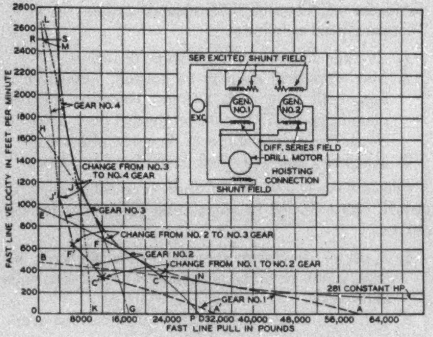

FIG. 2—COMBINATION 2

Assume two differential generators are being operated in parallel, driven by separate engines. If, for any reason one engine slows down, the voltage of its generator drops, causing a partial transfer of load to the other generator. This transfer is momentary and when stability is reached, the resultant voltage and kilowatt output of the slower generator is slightly reduced. The division of load on the generators is in proportion to the respective engine horse power output. Any difference in engine speeds causes an unequal division of load current between the generators, the machine running at the higher speed supplying the larger part of the current.

*Series Connection.* Successful operation of duplicate d-c generators in series is attained with either shunt-wound or differentially compound-wound types of generators.

If duplicate d-c generators are being operated in series and the speed of one engine decreases, the output of its generator decreases in proportion. As the current output is not affected, the available motor torque remains unchanged, but the motor speed is reduced in proportion to the decrease of terminal voltage. Regardless of the condition of operation, there is no transfer of load current between generators. However, both machines can become equally overloaded.

*2. Relative First Cost and Operating Charges.*

The first cost of the series connected and the parallel connected combinations should be practically the same. Experience has shown that if the equipments are properly designed for their operating voltages there will be no appreciable difference in operating cost.

*3. Relative Installation Cost.*

The only difference in the installation costs of either of the four combinations is in the wiring. Because the current is doubled when hoisting with the parallel-connected equipment, the wire to the drilling motor must be approximately double in size to that used for series-connected equipment, for the same voltage drop.

*4. Relative Safety.*

From a safety standpoint, there is very little advantage to be gained by the choice of either equipment. In both cases, the combined no-load voltage of either the hoisting or drilling connection is below 600 volts. As rubber covered wire used in these installations is rated at 600 volts with a safety factor of five, and as all live parts are normally protected, both connections are equally safe. In case of trouble the plant operator and not the drilling crew makes the necessary repairs.

As a specific example of voltage values of generators operating in series and in parallel the following may be considered. The combined no-load voltage of two generators in the series combination is approximately 580 volts. The no-load voltage of generators in the parallel-connection equipment is approximately 450 volts. The full-load voltage of the generators in each combination is 250 volts. If two generators designed for parallel operation were connected in series, the combined voltage would be unsafe but when the generators are designed for a particular connection, the combined no-load voltage of either connection is below 600 volts.

VIEW OF DERRICK FLOOR

Showing rotary table with upper end of dull stem, also front view of drawworks with driller, on the extreme left. The other four men are members of the rotary crew

*5. Choice of Size of Equipment.*

A comparison of characteristics might be made of equipment having any assumed value of horse power. In the comparison made here a power plant equipment consisting of two 200 hp engines driving 125-kw generators is chosen because this capacity is considered sufficient for present-day drilling.

The drilling motor, taking power from both engine-driven generating units when hoisting, should be designed to have a maximum output of 281 hp. This value represents the combined engine ratings less losses and auxiliary power. It is essential that the characteristics of the drilling motor and the generators be such that the prime mover will operate at its maximum output over the widest possible range of torque and speed.

Control Cabinet Located in Generator House Showing Meters and Auxiliary Switches

The horse power ratings of electrical equipment are the same for either of the combinations being considered; however, the electrical characteristics are widely different.

*6. Choice of Electrical Characteristics.*

*General.* One of the most important duties of any type or kind of equipment used for drilling oil wells is to hoist strings of drill pipe. It is, therefore, reasonable to assume that the best combination of generator and motor characteristics for such work is that in which the engines driving the generators will be loaded to their normal capacity for the maximum time of the hoisting cycle.

In order to make a true comparison of the characteristics of these various equipments and eliminate differences in types and ratings, their speed-torque characteristics are converted into fast-line speed and fast-line pull, (the fast line being the one wound directly on the hoisting drum) using the most advantageous drawworks sprocket ratios in each case. Plotting these values in the form of curves, together with a curve representing the net available constant engine output, results in a visual picture of the behavior of each equipment.

In order to convert these values to get fast-line speed and fast-line pull, it was necessary to assume average values for weights and dimensions of various rig parts. These are listed as follows:

1. Average diameter of hoist drum, 30 inches.
2. Maximum drill stem to be hoisted, 7,500 feet of 6-in. drill pipe with 8 lines, weighing 235,000 pounds, or 29,375 pounds on the fast line. This includes the weight of blocks, line, elevators, etc.
3. Maximum fast-line speed, 2,500 feet per minute.

*Calculations of Data for Curves.* The following procedure was followed in calculating the values for the curves.

1. A set of drawwork sprocket ratios is chosen by trial, which gives the best balance of fast-line pulls and speeds.
2. For each drum speed or gear ratio, various available fast-line speeds are assumed and converted into motor speeds.
3. The motor speeds are used to obtain the corresponding motor torques. These are taken from curves showing the speed and torque of the motors operating on the voltage of the generator used in the combination of equipment considered in each particular case.

Mud Pump and Mud Pump Motor

4. The pull, in pounds, for each fast-line speed is calculated.
5. The fast-line velocity-pull curves are then plotted, using the fast-line speed in (2) as ordinates and the pounds pull in (4) as abscissas.

The fast-line velocity-pull characteristics are calculated for each of the following combinations and the results plotted in the form of curves as designated.

TABLE I

| Combination | Type of generators | Generator connection | Type of motor | Fig. No. |
|---|---|---|---|---|
| No. 1 | Differential | Series | Shunt | 1 |
| No. 2 | Differential | Parallel | Shunt | 2 |
| No. 3 | Differential | Series | Compound | 3 |
| No. 4 | Shunt | Series | Compound | 4 |

## DERIVATION OF ELECTRIC MOTOR CHARACTERISTICS

The speed-torque characteristics of the No. 2 combination and the No. 3 combination were obtained from electrical manufacturers. The curves of the other two combinations were recalculated from manufacturers' curves of different ratings. These estimates are very close, however, and will not make an appreciable difference in the accuracy of the results.

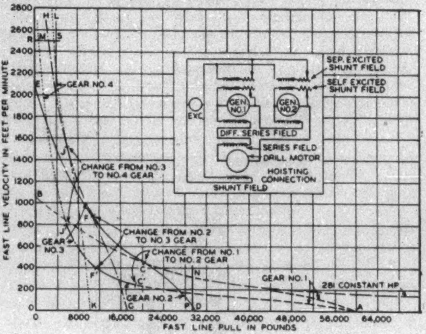

FIG. 3—COMBINATION 3

*Explanation of Curves.* For each of the four combinations a constant horse power curve *NS* (see Figs. 1, 2, 3 and 4) representing the net available constant prime mover output of 281 hp is first drawn, using fast-line speeds as ordinates and fast-line pulls as abscissas. As the product of velocity and pull is proportional to horse power, the area under this curve is proportional to the maximum energy which is expended with this constant output, and represents the characteristics of an ideal equipment having an infinite number of gear ratios. Therefore, since the area *NPORS*, in Figs. 1, 2, 3 and 4, within the limits previous specified, is the maximum obtainable, it will be considered 100 per cent. The velocity-pull characteristics of a four-speed drawworks are then drawn, using gear ratios which utilize the motor characteristics of each combination to the best advantage. In each figure, the characteristics of low-low or No. 1 gear is shown by curve *AB*, high-low or No. 2 gear by curve *DE*, low-high or No. 3 gear by curve *GH* and high-high or No. 4 gear by curve *KL*.

As the areas representing the energy expended by equipments driving four-speed drawworks, do not coincide at all points with the ideal area *NPORS*, the motor characteristics determine how closely it is approached.

In order to obtain maximum energy from any combination, it is necessary to change gears at definite values of fast-line pull as shown by points *C*, *F*, and *J* in Figs. 1, 2, 3 and 4. The energy from any of the combinations is proportional to the area *NPORSJFC* and, compared with the area under the ideal curve *NS*, is as follows for the various combinations:

TABLE II

| Combination | Per cent of area *NPORS* | Fig. No. |
|---|---|---|
| 1 | 91.3 | 1 |
| 2 | 96.1 | 2 |
| 3 | 99.7 | 3 |
| 4 | 99.4 | 4 |

On this basis of comparison, combinations 3 and 4 utilize the engine output to the best advantage.

Under ordinary conditions, it is rather difficult for the driller to know when to change gears, and unless they are shifted at the correct values of pull, hoisting time is lost. This is especially true of combinations 1 and 2 which have the flattest characteristic and show the smallest increase in speed with decrease of load. Combinations 3 and 4, however, have a rapidly rising characteristic and, even if the driller does not change gears at the correct pull, he does not lose much speed over a comparatively wide range of pull.

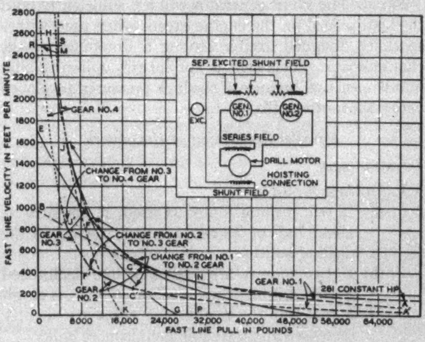

FIG. 4—COMBINATION 4

Another point to be considered is the pull which can be exerted by the various combinations when only one generator is used. It is sufficient to say that, in the series system, the fast-line pull is approximately the same, whether one or two generators are used. However, in the parallel system, the fast-line pull, when one generator is used, is approximately half that available when two generators are used, for the gear ratios selected.

The values of fast-line pull, under the conditions mentioned above, for the various combinations are as follows:

TABLE III

| Combination | Maximum fast-line pull in pounds | | Fig. No. |
|---|---|---|---|
| | One generator | Two generators | |
| No. 1 | 59,800 | 59,800 | 1 |
| No. 2 | 33,000 | 59,800 | 2 |
| No. 3 | 59,800 | 59,800 | 3 |
| No. 4 | 76,200 | 89,500 | 4 |

It is not improbable that one generating unit would be out of service when a full string of drill pipe is in the hole, in which case it would be necessary to increase the number of lines in the blocks if the parallel system as discussed were used, whereas, in the series system, no inconvenience would be caused except a reduction of 50 per cent in the hoisting speed.

## SUMMARY OF RELATIVE MERITS OF VARIOUS COMBINATIONS

### *Type of Generator*

*Differential.* The differential generator limits the load placed on the engine, limits the pull on the drilling line, and also limits the maximum pressure developed by the mud pump.

*Shunt.* The shunt generator will not sufficiently limit the load placed on the engine except when used with a specially designed exciter having a drooping voltage characteristic. This type is not entirely suited to mud pump operation because of the high pressures developed before the motor stalls.

### *Parallel Connection of Generators*

*Disadvantages.*

1. Drilling Motor.
   (a) If one drilling motor is used, it operates at about half of its rated capacity when in the drilling position.
   (b) If two motors are used and one declutched during drilling, the objection in 1 (a) is eliminated, but the installation costs are slightly increased and the equipment is more bulky.
2. The cross section of wire for armature circuits from the generators to the drilling motor must be double the size used in the series system.
3. The fast-line pull available, is reduced approximately 50 per cent when one generator is out of operation.

### *Series Generator Connection*

*Advantages.*

1. Drilling motor operates at its rated torque for either drilling or hoisting. The horse power capacity is doubled for hoisting by increased voltage.
2. Size of wire for armature circuits between generators and motor is one-half that of the parallel connection.
3. The fast-line pull available, is approximately the same with one generator as with two.

### *Type of Motor*

*Shunt.* The shunt-wound motor in itself has the disadvantage of a flat characteristic which gives very little speed variation over its operating range. However, this characteristic is caused to droop by the drooping voltage characteristic of the differential generators.

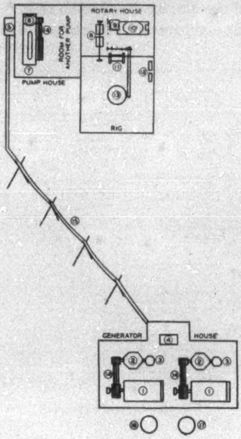

FIG. 5—LAYOUT FOR VARIABLE VOLTAGE OIL WELL DRILLING EQUIPMENT

1. 200 hp internal combustion engine
2. 125-kw d-c generator
3. 15-kw d-c exciter
4. Variable voltage control
5. Terminal box
6. 125-hp d-c mud-pump motor
7. Power-driven mud-pump
8. Master control
9. Reduction gear for drilling motor
10. 125/250-hp d-c drilling motor
11. Drawworks
12. D-c ammeters
13. Rotary table
14. "V" belt drive
15. Wiring between engine house and rig, carried on "X" supports
16. Water tank for engines
17. Fuel tank for engines

*Compound.* The compound motor in itself has the advantage of a steep characteristic which gives wide speed variations over its operating range.

## CONCLUSIONS

An analysis of this paper shows that all four combinations discussed can be used satisfactorily for the drilling of an oil well. However, the "Summary of the Relative Merits of the Various Combinations," shows that each equipment has its distinct advantages. Therefore, an operator should choose that equipment which would give him the best overall results.

## Discussion

**W. G. Taylor:** In his summary of the relative merits of the various combinations, Mr. Albrecht shows that the differential generator is preferable to the shunt generator, a conclusion with which I concur. However, his comparison of parallel with series connections is apparently disassociated from the question of type of generator used, and if this comparison is made with reference to the use of differential generators in each case, the conclusions which will be reached will be quite different.

In making such a comparison, it is necessary to base it on definite motor and generator voltages for each system. In the parallel system, to keep within the maximum voltage of 600 indicated by Mr. Albrecht, a rated voltage of 250 for motors and generators will meet this requirement, as the maximum no-load voltage with one or two generators will be approximately 450. In the series system, Mr. Albrecht states that the combined maximum voltage of two 250-volt differential generators would be unsafe. Furthermore, such a combination would impose a maximum voltage on the draw works motor which would too closely approach the inherent limits of satisfactory commutator design. Therefore, to keep within the indicated maximum of 600 volts requires the use of 125-volt generators and mud pump motors and a 250-volt draw works motor.

Therefore the comparison which follows is based on a parallel system with 250-volt differential generators and motors, and a series system with 125-volt differential generators and mud pump motors and a 250-volt draw works motor.

*Hoisting with Two Generators.* The voltage, current and torque characteristics of both systems will be identical, therefore giving the same performance characteristics in both cases.

The same size of cable will be required between generators and draw works motor in both systems.

*Hoisting with One Generator.* In considering the maximum pull which can be exerted by the various combinations when only one generator is used, Mr. Albrecht intimates that the parallel system has a practical disadvantage, in comparison with the series system, because this maximum pull is only half of that available with two generators or with the series system. He states this disadvantage as a necessity for increasing the number of lines in the blocks to lift a full string of drill pipe in the hole, in case one generating unit of the parallel system is out of service. As a matter of fact, however, this is not necessary under the conditions assumed and illustrated in Mr. Albrecht's discussion or in normal drilling practise generally.

The curves in Fig. 2 illustrate the characteristics of the parallel system applied to conditions in which the maximum weight to be lifted requires a fast-line pull of 29,375 lb. Although Mr. Albrecht has not explained it, curve *J'F'C'A'* represents the hoisting characteristic with only one generator. It will be noted that under this condition it requires a fast-line pull of over 32,000 lb to stall the motor, and the load of 29,375 lb will be lifted, with no increase in the number of lines, at a speed of about 75 or 80 ft per min, which is ample in such an emergency. Not only in this particular case with the parallel system is the available pull sufficient with only one generator, but in the normal application of this system this will be true generally. This is due to the fact that the first or lowest speed of the draw works is too slow over most of its range for regular hoisting service with two generators, and so a variable-voltage equipment would not be selected of such small capacity that it would require a more extended use of the lowest drum speed than that indicated in Fig. 2 to handle the heaviest loads with two generators. This means that an equipment with the parallel system, suitable in capacity to hoist the drill pipe with two generators at the fast speeds demanded by modern drilling practise, will be able to lift the heaviest load with one generator and thus get the drill pipe out of the hole in such an emergency with no increase in the number of lines in the tackle.

*Drilling with One Generator.* In the parallel system, the draw works motor will run under maximum load at full voltage and half of full load current, and at full speed.

In the series system, the draw works motor will run under this same load at half voltage, full current and at half speed. Because of the reduced speed, the self-ventilation will be less effective and the heating consequently higher.

With the same drilling load under consideration for each system, the horsepower demand will be the same in both cases. The parallel system will deliver it at half as much armature and line current as the series system, and therefore with less copper loss and consequently higher efficiency.

*Mud Pump Operation.* In the parallel system, the mud pump motors will have the same rated voltage as the draw works motor, and so they can be and often are duplicates. This makes a mud pump motor available to replace the draw works motor in an emergency if the latter goes out of service.

In the series system, the 125-volt mud pump motor is not a duplicate of the 250-volt draw works motor and so cannot be used in such an emergency, nor will it use the same repair parts. Furthermore the wiring to the 125-volt motor must have twice the current capacity necessary for the corresponding wiring in the parallel system.

*Conclusion.* This definite comparison shows that the parallel system with differential generators is at least equal to the series system in operating characteristics, and is preferable from the standpoint of efficiency, interchangeability, wiring, repairs and application to the standard drilling rig with minimum mechanical changes.

Finally, there is one other practical consideration which I desire to mention as an important influence in the choice of equipments described by Mr. Albrecht, that being with reference to the use of a compound wound motor on the draw works. This motor must be reversed frequently when hoisting drill pipe, and if it is compound wound, suitable control equipment must be furnished to reverse the series field. This adds materially to the first cost, as the currents to be handled are heavy, and it increases the maintenance and departs from the simplicity of the control of the shunt-wound separately excited motor. In view of the comparatively small advantages of a compound winding as outlined by Mr. Albrecht, this complication scarcely seems warranted on a rotary drilling rig.

**A. H. Albrecht:**

1. Mr. Taylor's initial assumption that the comparison of parallel with series connections is disassociated from the type of generator used is in error; Table I of the paper clearly sets forth the type of generators, generator connection, and type of motor for each combination discussed.

2. Mr. Taylor quotes from the paper as follows: "The combined maximum voltage of two 250-volt differential generators would be unsafe." This statement is misleading as he did not complete the sentence. The complete quotation is as follows, "If two generators designed for parallel operation were connected in series, the combined voltage would be unsafe *but* when the generators are designed for a particular connection, the combined no-load voltage of either connection is below 600 volts." The author further states that the full load voltage of the generators in each combination is 250 volts. In other words, two differential generators, each rated 250 volts full load, if properly designed, can be operated in series with a total no-load voltage of less than 600 volts.

3. Mr. Taylor states that, "Therefore, the comparison which follows is based on a parallel system with 250-volt differential generators and motors, and a series system with 125-volt differential generators and mud pump motors and a 250-volt drawworks motor." This comparison also is misleading as the series combinations discussed in the original paper are based on systems utilizing 250-volt generators and a 250/500-volt drawworks

motor. Two of the series systems actually were built and the data used in the paper were based on manufacturer's tests of these equipments.

4. *Hoisting with two generators:* On account of the erroneous assumption discussed above, Mr. Taylor states that the voltage, current, and torque characteristics of both systems will be identical, therefore giving the same performance characteristics in both cases, the same size of cable being required between generators and drawworks motor in both systems. The performance characteristics are not identical but are the same as originally stated by the author. Likewise, the size of cable required for the parallel connection will be twice the size required for the series connection.

5. *Hoisting with one generator:* Mr. Taylor is correct in stating that in Fig. 2, one generator is able to pull the specified weight at about 75 or 80 feet per minute with no increase in the number of lines. However, when the low efficiencies of oil field hoisting equipment and the necessity of meeting such conditions as stuck drill pipe are considered, having maximum pull available at all times is highly desirable.

6. It is true that self-ventilation will be less effective with the series system than with the parallel system when drilling with one generator. However, drilling motors should be provided with forced ventilation for safety so this objection is eliminated.

7. As stated by Mr. Taylor, the mud pump motors, in the parallel system may have the same rating as the drawworks motor which allows interchangeability in case of emergency. However, in practise the mud pump motor requires only about one-half as much horsepower as the drilling motor. Therefore, if these motors are made the same size, the mud pump motors would be larger than necessary or else the drilling motor would be smaller than required.

8. Since the original paper presumed 250-volt mud pump motors in the series system, the wiring and current is the same as for the corresponding parallel system.

9. It seems as though the first paragraph of Mr. Taylor's conclusion is irrevelant since his original assumption is in error. He has not shown in his discussion that either system has any advantage over the other in applying it to the standard drilling rig.

10. In regard to the use of a compound wound motor on the drawworks: If a compound motor were reversed as stated by Mr. Taylor, his arguments would be true. However, it is not necessary to use the compounding in reversing. Consequently, it is necessary only to cut out the series winding by a suitable explosion proof contactor placed on the motor frame and these objections have been eliminated.

To the author's knowledge three wells have been drilled with a compound motor using such a contactor, without experiencing any difficulties. The increase in first cost is negligible. Two additional control wires from the rig controller to the drilling motor, is all that is required over the shunt-wound separately excited motor.

In view of the foregoing discussion, the author feels that the advantages and disadvantages of the parallel and series generator connections as stated in the original paper still hold.

# Recent Developments in Electronic Devices for Industrial Control

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## INTRODUCTION

SINCE the development of the thermionic amplifier tube, the possibility of using this tube in industrial control equipment has appealed strongly to design engineers. Outside the train control field, however, no serious attempts were made up to a few years ago, actually to install electronic industrial control devices. The reason for this was chiefly that tubes, having sufficient capacity to handle industrial control operations without interposing mechanical relays, were not previously available. With the perfection of the high current, high vacuum tube, with 320 milliamperes capacity, and especially after the development of the grid glow tube with capacity up to 25 amperes, the industrial application of electronic tubes was given added impetus, and during the last few years considerable experimenting has been done to adapt electronic equipment to various industrial control and regulating processes.

At the present time, several successful installations in different branches of industry testify to the superiority of electronic control compared to the conventional electro-mechanical type of equipment. For this reason, the future field for electronic control devices will not only be to perform functions which cannot be accomplished by electro-mechanical or other means; but will also be to supplant electro-mechanical control and regulating devices, especially in applications where high sensitivity and quick response are considered prime requisites.

## GENERAL CHARACTERISTIC OF ELECTRONIC CONTROL DEVICES COMPARED WITH OTHER TYPES OF CONTROL EQUIPMENT

In comparing electronic control equipment with other types of control equipment, several features are readily recognized which make the application of electronic devices desirable from an industrial point of view. The outstanding feature of electronic equipment is the high sensitivity which can be attained without the use of sensitively balanced moving parts. Voltage regulating equipment may be mentioned as an example. Electro-mechanical regulators in most cases need dashpots attached to a sensitively balanced lever system in order to provide damping and to provide the required anti-hunting characteristic. It is obvious that a certain amount of friction will always be present in these dashpots, and the friction may develop to such an extent as to impair the regulator sensitivity unless the dashpot is maintained in proper operating condition. In electronic regulating equipment, as mentioned later in this paper, the anti-hunting function is accomplished by means of a condenser which operates as a friction-free dashpot, and which does not require maintenance.

The absence of moving parts, and consequently, the absence of mechanical inertia, gives electronic equipment an extremely quick response characteristic. This feature is of utmost importance in many industrial control applications where the impulse initiating the control sequence may have a duration of 0.001 second or less. Equipment for control of register in paper cutter applications is a typical example of equipment of this kind.

The absence of mechanical inertia makes electronic equipment ideally suited to applications where the device may be tilted at an angle when operating. A specific example of such installations is the application of voltage regulators on board ship, where minor variations in regulated voltage are liable to occur, when electro-mechanical regulators are used, if the vessel is rolling heavily; while electronic type regulators will not be affected whatsoever.

In several industrial control applications, the controlling force whether mechanical or electrical, may be of such low energy level that its direct application to electro-mechanical control devices will not give the required sensitivity due to the relatively high amount of energy required to operate this type of equipment. Since the energy required to control an electronic amplifier tube may be 1 $\mu$w or less, low energy level control applications can always be worked out satisfactorily by means of electronic equipment. A particular class of low energy level control includes those applications where no contact, either electrical or mechanical can be made with the quantity under control. In that case, practically, the energy level is zero. In such applications positive control can however, frequently be accomplished by means of a light beam, a photocell and associated amplifying equipment. Specific examples of this type of control is outlined later in this paper in connection with alkalinity control and plate glass width control.

Among other desirable features of electronic control equipment may be pointed out the small amount of maintenance required to keep the equipment in proper operating condition. There are no moving parts to be oiled and adjusted for wear, and no contacts to be filed to remove the effect of arcing, as in electro-mechanical control devices. The only maintenance required on a properly designed electronic control device is the replacement of tubes at the end of the useful tube life;

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an operation which is accomplished within a few seconds time. Another feature of electronic control which in certain applications may be considered a desirable one is its freedom from noise. In this connection should also be mentioned the absence of radio interference with most types of electronic equipment. A typical example is the electronic voltage regulator for direct current generators, as compared to the vibrating type voltage regulator. The problem of radio interference in connection with direct current control equipment is now being given serious consideration and undoubtedly in the future there will arise occasions where freedom from radio interference will be a point of considerable interest.

Due to the small amount of energy required to control electronic devices, manual control can be accomplished by means of small radio type potentiometers 1½ in. in diameter. This makes it possible to design very compact miniature control panels for various types of process control, and, if desirable the complete control unit may be built into a portable box arranged with a plug for connection to control receptacles located at various strategic points.

There are two other features of electronic type control equipment which must be considered in order to get a true picture of the relative merit of the two types of control. One is the apparent fragility of the electronic tubes, the other is the necessity of occasional tube replacement. Experience with various types of electronic applications indicates however, that the possibility of tube breakage is rather remote provided reasonable care is exercised in handling the tubes. The life of electronic tubes, at rated current, varies between 2,000 and 5,000 operating hours for grid glow tubes, and between 3,500 and 10,000 operating hours for high vacuum tubes. By operating the tubes below the rated current considerably increased life is obtained. As previously mentioned, replacement of tubes can be accomplished within a few seconds time and from a continuity of service point of view, therefore, the necessity of tube replacement is no serious drawback.

In deciding whether to apply electronic control equipment or to apply electro-mechanical or other types of equipment, in a particular installation, the yearly savings due to improved operation should be credited to the electronic side, and the yearly cost of tube replacement should be balanced against the decreased maintenance cost. In many industrial installations it will be found that the cost of tube replacement is insignificant compared to the increased profits due to the higher uniformity of the product, and the consequent decrease in percentage rejections.

## ELECTRONIC TIME DELAY RELAYS

The combination of an electronic tube and a condenser discharge circuit provides the fundamental circuit for a time delay relay which has all the desirable features of the various types of electro-mechanical relays now on the market, and which does not have any of the less desirable features of the electro-mechanical devices.

Electro-mechanical time delay relays may be classified in 5 different groups according to the principle of operation as follows:

1. *Relays With Dashpot*
   - (a) Advantages: Simplicity.
   - (b) Disadvantages: Maximum time delay approximately 10 seconds. The time delay is dependent upon the supply voltage. The time delay is affected by temperature changes due to variations in dashpot damping. Friction may develop in the dashpot with consequent change in time delay. Instantaneous reset cannot be obtained without mechanical complications.
2. *Escapement Relay*
   - (a) Advantages: No temperature error. Instantaneous reset.
   - (b)Disadvantages: The relay is subject to mechanical wear. The relay is noisy. Time delay is limited to approximately 10 seconds.
3. *Motor-Operated Gear Train Relay*
   - (a) Advantages: Time delay adjustable from 30 seconds to 4 minutes.
   - (b) Disadvantages: Expensive. Mechanically complicated.
4. *Flux Decay Type Relays*
   - (a) Advantages: Instantaneous reset. Inexpensive.
   - (b) Disadvantages: Requires direct current for operation. Maximum time delay 8 seconds.
5. *Thermal Relays*
   - (a) Advantages: Inexpensive.
   - (b) Disadvantages: Not very accurate. No instantaneous reset.

The electronic type time delay relay shown in Fig. 1 has all the desirable features of the electro-mechanical type relays previously referred to, and does not have any of the undesirable characteristics.

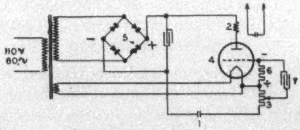

FIG. 1—ELECTRONIC TYPE TIME DELAY RELAY ELEMENTARY DIAGRAM

Referring to Fig. 1, a high vacuum amplifier tube 4 is connected in series with a relay 2 and a potentiometer 3 across the direct current output terminals of rectox 5. When the initiating contacts 1 close, the plate voltage is applied to tube 4, and the current through the coil of relay 2 and through potentiometer 3 starts to build up. The resulting increasing voltage drop across potentiometer 3 will cause a charging current to flow through resistor 6 to condenser 7. This charging current will produce a voltage drop across resistor 6 with a polarity as shown in Fig. 1. This voltage drop will give the grid of tube 4 a negative bias in relation to the cathode of the tube, and for this reason the rate of change of current through tube 4 and consequently, relay 2 will increase slowly. After a predetermined time, dependent upon the adjustment of potentiometer 3, the current through relay 2 will be high enough to operate the relay. The time interval between closure of contacts 1 and operation of relay 2 may be adjusted from zero to maximum by adjusting the movable contact of potentiometer 3 downwards.

The maximum time delay obtainable with the electronic relay is proportional to the product *RC*, where *R* is the resistance of resistor 6 in ohms, and *C* is the capacity of condenser 7 in farads. By adjusting potentiometer 3 any value of time delay between zero and maximum may be obtained. In order to obtain sufficient sensitivity in time delay adjustment, various values of resistor 6 should be used for different time delay ranges. Since resistor 6 is a small grid leak type resistor, the adaptation of the relay to various time delay ranges can be easily accomplished. The maximum time delay of this equipment is approximately 3 minutes and the minimum time delay 0.05 sec. The time delay for any definite adjustment of potentiometer 3 remains constant within ± 5 per cent. The equipment operates from a 110-volt, 60-cycle source, and requires approximately 10 volt-amperes for its operation. The time delay does not vary more than 1 per cent for a-c supply voltage changes within the commercial range of ± 5 per cent.

The electronic type time delay relay is particularly suited to timing applications where frequent adjustment of the time delay is required. A typical application of this nature is in connection with spot welding equipment, where a relay circuit as shown in Fig. 1 meets the desired requirements of accuracy and adjustability.

## Register Control

In various industrial processes it is required to synchronize or register two separate control operations so that space and time relationship between the two remains constant. To illustrate this type of application, the problem of maintaining the register of the knife in paper cutter applications will be outlined. In continuous cutter applications the material to be cut is fed to the cutter from a reel by means of a pair of draw rolls. The cutter is usually of the rotating type and is driven from the same motor as the draw rolls. If there is a printed design on the material, it is desirable to maintain the register of the cut in relation to the printed design. This is obtained by either adjusting the speed of the draw rolls in relation to the cutter speed permanently, or by changing the draw roll speed temporarily. In the latter case the adjustment is equivalent to a space correction of the material to be cut, in relation to the cutter knife.

Present paper cutters require usually three operators for successful operation. One of the operators is kept continuously busy regulating the speed of the draw rolls, another operator stacks the paper when it leaves the cutter, and the third operator sorts the sheets and arranges for further trimming those sheets which have been incorrectly cut. The work of the operator regulating the draw roll speed is exceedingly monotonous, and from time to time he will find the knife cutting the paper considerably off the printed spot used for indicating the proper position of the cut. This results in considerable waste of paper and considerable expense in trimming the sheets to their proper length. By applying photoelectric control of the draw rolls the amount of wasted paper, which at present may be up to 15 per cent or more will be considerably reduced and the number of operators in most cases can be reduced from 3 to 2.

The photoelectric paper register control device operates on the general principle of synchronizing a spot printed on the paper with a pair of cams attached to the rotary cutter shaft. When the cut is in register the contacts operated by the rotating cams do not engage when the photo cell impulse is obtained. For this reason no relay action is obtained. If however, the cut is slightly ahead of the spot or behind the spot one pair of contacts will engage at the instant of photo cell impulse, and by means of suitable amplifying equipment a control relay will be closed and will operate the draw roll speed adjuster or the draw roll position adjuster, in order to bring the paper back in register with the knife.

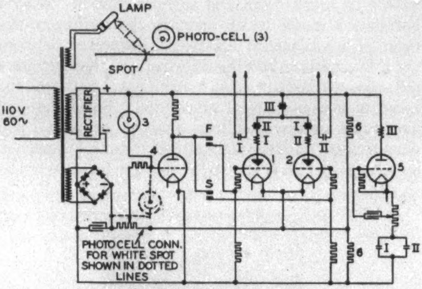

Fig. 2—Elementary Diagram of Electronic Register Control Equipment

In some applications the slip of the paper in relation to the draw rolls is zero or practically constant so that when the speed ratio between the cutter and the draw rolls is once adjusted the entire control can be obtained by means of position control. In other applications the slip varies considerably due to changing paper characteristic, and a speed ratio change as well as a position change is required in order to get satisfactory operation.

In Fig. 2 is shown an elementary diagram of an electronic register control device which will operate either from an impulse received from a white, yellow or red spot on a dark background, or from a dark spot on a white, yellow or red background. The equipment may be arranged for operation with transmitted light when the transparency of the paper is high, or with reflected light when the paper is opaque. A photocell 3 is connected to control the amplifier tube 4 so that when the spot intercepts the beam of light the current through the amplifier tube will decrease. The grid glow tubes 1 and 2 are connected in series with their respective relays I and II, and by means of the voltage divider 6, the grids of tubes 1 and 2 are given a definite negative bias in relation to the cathodes so that tubes 1 and 2 normally will not carry current. Contacts *F* and *S* are operated by the cams connected to the rotating cutter knife, and are adjusted so that the contacts are open when the spot intercepts the light beam if the cutter knife is in register with the design on the paper. If the draw rolls are operating too fast contacts *F* will be closed at the instant of photocell impulse, and consequently, since the current of tube 4 has decreased due to the photocell action, a positive bias will be impressed on the grid of grid glow tube 1, thus causing tube 1 to break down and energize relay I. Relay I energizes a motor which operates the stationary element of a mechanical differential connected between the driving motor and the draw rolls, so that the draw roll speed will be reduced an amount equal to the output speed of the mechanical differential. Since the grid glow tubes are energized from a d-c source, relay I will remain closed until the plate circuit of tube 1 is opened by relay III which is controlled by tube 5 connected in a time delay circuit similar to Fig. 1. If the paper is lagging in relation to the cutter knife contacts *S* will be closed when the photocell impulse occurs and relay II will close to operate the mechanical differential in the reverse direction.

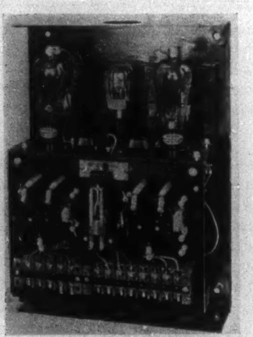

FIG. 3—ELECTRONIC REGISTER CONTROLLER

Due to the application of grid glow tubes the response of this equipment is practically instantaneous so that a sensitivity of 1/16 inch can be obtained with a spot 1/8 inch wide for paper speeds in excess of 500 feet per minute. The equipment operates from a 110-volt, 60-cycle source, and the performance will not be affected by voltage changes within ± 5 per cent. The equipment can be advantageously applied to a variety of cutter installations and its application is not limited to paper cutter applications. A promising field for this type of equipment is the register control of machines for the manufacture of bags of paper, cellophane, cloth or other types of material.

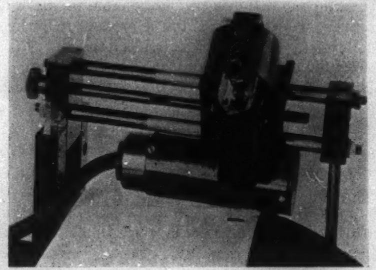

FIG. 4—LIGHT SOURCE AND PHOTO-CELL ASSEMBLY FOR REFLECTED LIGHT APPLICATION

An illustration of the control cabinet is shown in Fig. 3. The light source and photo-cell assembly which is used in reflected-light applications is shown in Fig. 4.

## ELECTRONIC SPEED AND VOLTAGE REGULATORS FOR DIRECT-CURRENT MACHINES

The various electro-mechanical type voltage regulators now on the market have a definite insensitivity zone due to unavoidable friction in dashpots, bearings and other moving parts. By proper design and through careful maintenance the regulator sensitivity however can be kept within a zone of ± 0.5 to 1 per cent which is entirely satisfactory for most industrial applications. In the average industrial regulator application the regulator response is usually not considered to be of much consequence unless lights are connected to the circuits; but there are applications for example in motion picture studios where this feature is of paramount importance. The speed of response of electro-mechanical type voltage regulators is limited by the inertia of levers and other moving parts of the device, and not considering the rheostatic type voltage regulators, the speed of response is also limited by the inherent characteristic of the anti-hunting means.

Anti-hunting is required in any voltage regulating device due to the electrical inertia of the exciter and the generator, and the success of a voltage regulator depends to a large extent upon the proper selection of the anti-hunting means. Through the anti-hunting means a corrective force, either electrical or mechanical, is applied to the primary element of the voltage regulator during the regulating period to counteract the corrective regulator action, so that at all times the rate of voltage correction is proportional to the error in voltage. An electronic type voltage regulator for direct-current generators which meets these requirements of ideal anti-hunting characteristics has recently been developed.

Exhaustive tests seem to prove that in respect to sensitivity and response this regulator is superior to any of the electro-mechanical type voltage regulators previously available.

The schematic diagram of the electronic voltage regulator is shown in Fig. 5. The regulated voltage obtained from potentiometer 5 is bucked against the constant voltage from battery 4, and the voltage difference is applied to the grid of screen grid tube 2.

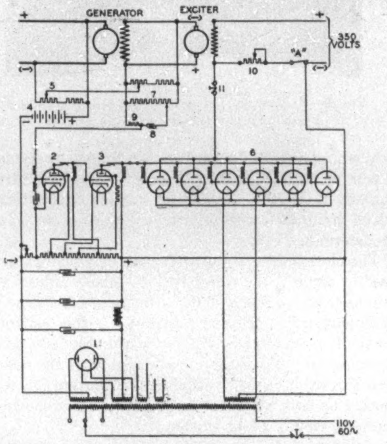

FIG. 5—SCHEMATIC DIAGRAM OF ELECTRONIC VOLTAGE REGULATOR

The regulator, when in operation, will tend to maintain this voltage difference constant at 1.7 volts. Any deviation in this voltage difference is amplified by tube 3 and the power tubes 6, so that a minute change in regulated voltage will cause a considerable change in the current in the exciter field winding which is connected in series with the power tubes across a 350-volt direct-current source. To prevent hunting resistor 9 is connected in series with condenser 8 across potentiometer 7 which is connected to the exciter armature terminals. When the exciter armature voltage is decreasing as a result of regulator action when load is disconnected from the generator, condenser 8 will discharge through resistor 9, and the voltage drop thus created will oppose the initial voltage change on the grid of tube 2 caused by the increase in regulated voltage; and therefore stabilize the regulator operation.

The sensitivity of the electronic regulator is ± 0.2-volt or better, and the regulator will bring the regulated voltage back to normal in from 2 to 5 cycles as indicated by the oscillogram in Fig. 6 if the exciter is omitted and the power tubes are connected directly in series with the generator field winding. During this test full load was connected to a 5-kw shunt wound generator. In Fig. 7 is shown an oscillogram of the same load conditions, with a ½-kw shunt wound exciter used to supply the excitation for the generator. The speed of response of the regulator is apparent from Fig. 6, which indicates that the regulator tends to correct for the variations in regulated voltage due to commutator ripples, which were rather pronounced on this particular generator. The action of the anti-hunting circuit is indicated in Fig. 7. It may be seen that due to the anti-hunting action the exciter field current starts to decrease before the regulated voltage has reached the normal value.

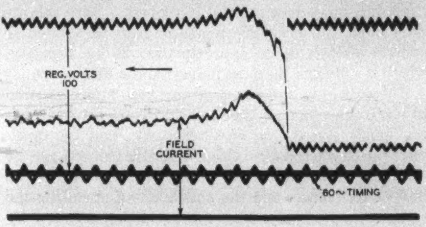

FIG. 6—RESPONSE OF ELECTRONIC VOLTAGE REGULATOR WITHOUT EXCITER

As shown in Fig. 5, the field rheostat for manual control 10 is connected so that when switch *A* is closed the field rheostat will be in parallel with the power tubes. In order to transfer from automatic to manual control, rheostat 10 is turned in and switch *A* is closed. The rheostat is then gradually turned out until the regulated voltage is 0.5-volt higher than normal, thus indicating that the current through the power tubes is zero. The field switch 11 may now be opened and manual control obtained by means of rheostat 10.

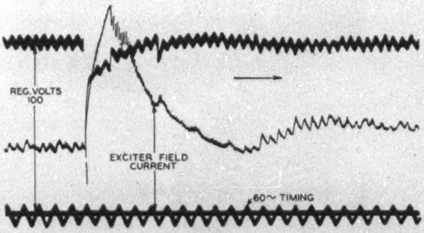

FIG. 7—RESPONSE OF ELECTRONIC VOLTAGE REGULATOR WITH EXCITER

The regulating range of the six RJ-563 tubes when new is 0.15 ampere to 1.2 amperes. At the end of the useful tube life the filament emission will, however, be slightly decreased, and for this reason the regulator is applied on the basis of a maximum current output of 0.9 ampere, thus giving a regulating range of 0.75 ampere. If the maximum exciter field current exceeds 0.9 ampere, switch *A* is not supplied, rheostat 10 is permanently connected in parallel with the RJ-563 tubes, and is designed to carry the no-load exciter field current minus the minimum tube current 0.15 ampere. With this arrangement the electronic regulator may be applied to control exciters up to approximately 20 kw capacity, which is sufficient for most industrial d-c generators.

The advantages of the electronic regulator compared to electro-mechanical type regulators are primarily, as previously stated, the high sensitivity and the quick response characteristic. Other desirable features are the simplicity of operation, the absence of maintenance, no radio interference, and the possibility of operating the equipment on board ship without being affected by rolling.

The electronic regulator has been successfully applied as a speed regulator for a single motor paper machine drive. In this case the motor was connected for armature control by means of a variable voltage generator, and the regulator was connected in the field circuit of the exciter which supplied excitation for the generator. A pilot generator geared to the motor served as the voltage indicator. In Fig. 8 is shown the electronic voltage regulator with covers removed. Fig. 9 shows the regulator mounted on a control board for a single motor drive having a 12 to 1 speed range.

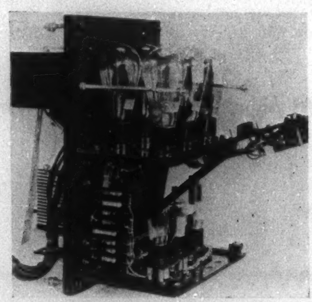

FIG. 8—ELECTRONIC VOLTAGE REGULATOR WITH COVERS REMOVED

## ELECTRONIC MOTOR STARTER

In applications where variable speed control of d-c motors over a wide speed range is needed, the conventional method of control is to supply a motor-generator set and to vary the generator voltage. An electronic motor starter shown in Fig. 10 which has recently been developed provides the means for adjustable speed control of d-c motors with an alternating current supply source. The electronic motor starter is equipped with phase shift controlled grid glow power tubes which are connected to supply armature voltage for the motor. A smooth armature voltage control during the entire range from zero to maximum is obtainable. The motor field is supplied with a constant d-c voltage by means of a pair of rectifier tubes. A desirable feature of this equipment is the automatic starting characteristic which limits the current during the starting period to a predetermined value.

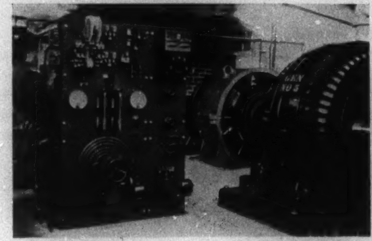

FIG. 9—ELECTRONIC SPEED REGULATOR INSTALLATION. SINGLE MOTOR PAPER MACHINE DRIVE

The electronic motor starter may be advantageously used in applications where frequent speed adjustments are made and where a smooth starting characteristic is of importance. A typical example is the control of manually operated coil winding machines where abrupt speed control may cause a wire break. At the present time this equipment is available for armature control of motors up to 5 hp, 230 volts. In Fig. 10 is shown an exploded view of a 3-hp starter.

## MISCELLANEOUS PHOTOELECTRIC CONTROL APPLICATIONS

The photoelectric cell with associated electronic equipment has long been extensively used for indicating and regulating purposes in various industrial processes, where the application of mechanical or electrical indicating devices would have been impractical. The use of photoelectric equipment for counting, sorting and inspection is thus rapidly increasing. Photoelectric equipment is often the only solution in counting applications where the objects to be counted cannot be arranged to operate mechanical counting devices due to the fragility of the material, due to the high temperature of the material, or due to the possibility of scratching a freshly painted surface. If the object to be counted is metallic, electrical circuits applying variations in capacity or inductance may be used; but in most cases it will be found that a photoelectric relay in connection with a light beam will give a more reliable indication.

If the object is fragile and non-metallic the application of photoelectric equipment is often the only solution for a successful installation. Photoelectric counting equipment is now being used commercially to count automobiles, sheets of paper, hot steel ingots, theatre patrons, incandescent lamp bases and a diversity of other objects.

Photoelectric equipment has been widely applied to initiate control operations where mechanical indicating means would not have been adequate. Photoelectric relays have thus been applied in paper mills as a paper break indicator, in steel mills to initiate shearing operations and to control soaking pit covers, and photoelectric equipment is extensively applied in elevator operation to prevent the closing of the elevator doors if a passenger is standing in the doorway. A manufacturer of window glass was confronted with the problem of indicating whether the glass sheet in leaving the oven had the correct width. Since the glass was plastic and red hot mechanical indicating means could not be used; photoelectric relays were installed and gave excellent service.

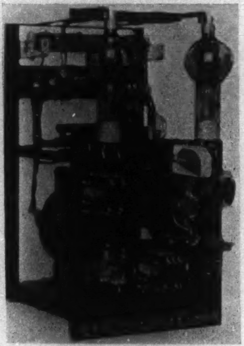
FIG. 10—3-HP ELECTRONIC MOTOR STARTER

Photoelectric lighting control relays are becoming popular as a means for controlling the illumination in offices and factory aisles, and experience with such applications indicates that frequently considerable savings in power consumption as well as increased production can be gained by the application of this device.

Photoelectric tubes in connection with amplifiers can be used to record small variations in light transmission through various substances. A commercial application of this is in the form of the photoelectric smoke indicator and recorder which may be applied to record the density of the smoke in the stack, and thus give an indication of the firing conditions. A similar application in a different field is the photoelectric indicator and regulator for concentration control. This equipment has been used to control the alkalinity of a copper solution in a copper refining process. Two photoelectric cells are connected in a wheatstone bridge circuit to control electronic amplifying equipment. The photocells are illuminated from the same light source. The light beam directed on one photocell is intercepted by a glass tube containing a sample solution having the desired alkalinity. The light beam illuminating the other photocell is intercepted by another glass tube through which flows the solution as used in the refining process. When the alkalinity changes, the color of the solution will change so that the balance of the wheatstone bridge is disturbed and through the amplifying system control relays are initiated which will change the speed of the lime feeding motor so that the alkalinity of the copper solution will be brought back within the proper limits. This scheme is described in more detail in a paper by J. V. Alfriend, Jr. (see page 512 of this issue).

The use of photoelectric equipment for sorting and inspection is increasing rapidly, and numerous applications in this field are working entirely satisfactory. The equipment may be arranged to initiate control relays which will remove from the production line an object which does not meet the specifications. For example, tin foil wrapped packages may be inspected by light reflection for proper labeling. If the paper label is in position the light will be reflected from the label and will be of low intensity, and the package will be carried forward on the conveyor. However, if the label is not placed properly, or is missing, the reflected light intensity is of high order and the control relays will be operated to divert the package.

In a similar manner inspection may be made for spots, holes or variations in color, although color inspection is a somewhat more difficult problem since the characteristic of the surface, whether flat or glossy, introduces complications.

The preceding paragraphs are not intended to cover the entire range of possibilities for profitable application of photoelectric equipment in the industrial field; but are merely intended to point out characteristic applications of light-sensitive equipment, in order to show its universal adaptability to almost any control problem which may be faced by industrial engineers.

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## Discussion

**R. E. Hellmund:** Mr. Gulliksen's paper is new and additional evidence of the great versatility of electronic devices in industry. In fact it can truthfully be stated that aside from their many possible functions in the generation, control and conversion of electric power, these devices and their circuits can take the place of the more important human senses such as seeing, hearing and feeling; in the latter case they even excell the human being and equal, through capacity effects, the ability of the bat to feel the presence of objects without actually touching them. The other human senses, taste and smell, are usually of lesser importance in industry, but more recently the tasting of fruit by electrically metering and recording its acidity by the use of electronic devices and circuits appears to be practicable and I believe under certain conditions the detection of odors by these means has been considered a possibility. As far as industrial processes and operations are concerned, the electronic devices offer possibilities of indicating, metering, recording and in many cases regulating with a high degree of sensitivity and accuracy and if desirable at or from remote locations such values, quantities and properties as:

Dimensions
Weight
Volume
Numbers
Position
Liquid Level
Density
Pressure
Light
Color
Opaqueness
Transparency
Sound and Vibration
Speed
Acceleration
Strength of Material
Mechanical Stresses
Time and Frequency
Temperature

Furthermore such functions as adding, subtracting, subdividing, inspecting, noise analyzing, timing and many others can be carried out or governed by means of electronic devices and circuits.

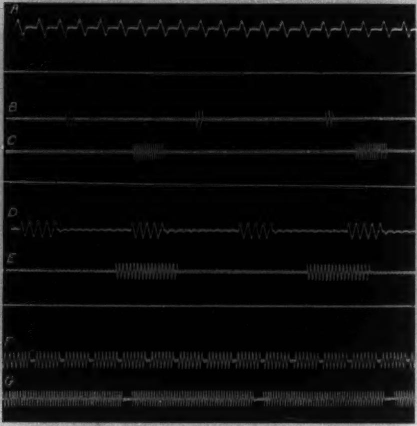

FIG. 1—OSCILLOGRAMS ILLUSTRATING RANGE OF CONTROL TO BE OBTAINED WITH GENERAL ELECTRIC CR7503-B2 THYRATRON-TUBE CONTROL FOR RESISTANCE WELDING MACHINES

*A*—1 cycle on, 1 cycle off
*B*—2 cycles on, 34 cycles off
*C*—15 cycles on, 95 cycles off
*D*—4 cycles on, 10 cycles off
*E*—17 cycles on, 36 cycles off
*F*—7 cycles on, 1 cycle off
*G*—47 cycles on, 4 cycles off

In view of the fact that many of these almost unlimited possibilities have been known for quite some time, the question is raised why the extent of the use of electronic devices in industry so far is, after all, very limited; to many this is most disappointing. Aside from the natural influence of the business depression and a certain reluctance to use new devices because of unfamiliarity with, and prejudice against them the answer to this question can be summed up in the one word "economics." Irksome as it may be to the enthusiast for the possibilities of these devices, economics will, in the best analysis, always be the governing factor. In the first place, while the electronic tube and its circuits are the parts making the particular device possible it must be appreciated that they are in many cases as far as the manufacturing and development cost is concerned, but a rather minor part of the entire device. The control of register in cutter applications described in Mr. Gulliksen's paper is a good example which shows the extensive and costly development required, in addition to the light sensitive tube proper, to accomplish the results. Naturally such expenses cannot be incurred unless they are economically justified by the particular application, either on account of extensive expected use and consequent quantity production or because of unusual benefits to the industry using the device. In many other applications the introduction of tubes has been retarded since the same result can under present conditions be accomplished by other means at a somewhat lower cost; an example of this kind is the motor control described in the paper. This condition is not necessarily inherent and permanent, but merely due to the fact that new tubes, now manufactured in small quantities have to compete with older highly developed and standardized devices. This condition can change only gradually as increased production brings about reduced costs which in turn will broaden the economic field of application and further reduce the costs.

These remarks, while explaining the present situation are by no means intended to dampen the enthusiasm about the possibilities of electronic devices in industry. Largely ignoring the present economics and gambling on the future, the designers have gone a long way in developing numerous applications at very considerable expense. It is now to be hoped that the users take an equally progressive attitude and at least partly discount slight economic handicaps as they appear at this time. Such an attitude can be well justified, because there are very frequently intangible advantages, which only become apparent after initial use. In this connection the early days of industrial electric heating may be recalled. The principal point then under discussion was the cost of electrical heat units as compared with fuel heat units and from this point of view the comparison did not look very favorable to electric heat. Since then so many advantages of electric heat such as automatic control, improved quality, reduced rejects, improved working conditions, possibilities of continuous flow production, etc., have become apparent that the heat economy has become of secondary importance in many cases. Quite similar conditions are already becoming apparent in many of the tube applications and industry as a whole is likely to benefit materially by an open minded progressive policy towards this new tool even in cases when the factors which

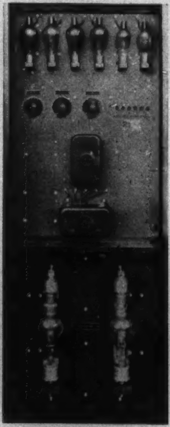

FIG. 2—THYRATRON CONTROL FOR RESISTANCE WELDING MACHINES WITH THYRATRON SYNCHRONOUS TIMER

are known and subject to figures at this time do not definitely show great economic advantages.

**W. R. King:** Concerning the description of the electronic time delay relay and particularly the statement referring to its use in connection with spot welding machines, I should like to point out that the successful welding of some materials depends upon the accurate timing of the application of power for periods as short as one or two cycles. This is particularly true in the case of many of the alloys being used at present. Mechanical interrupters and magnetic contactors are unsuited for this service, first, because of the inaccuracies inherent to such mechanical devices, and second, because they cannot readily be operated in synchronism with the system frequency. An electron tube system has been developed for the accurate control of resistance welding machines up to several hundred kilovolts. This system operates without mechanical contacts in the control circuit to control accurately the flow of current for periods as short as one cycle.

The system operates as follows:

The primary of a series transformer is connected in series with the primary of the welding transformer. Two power size thyratron tubes are connected to the secondary of the series transformer. When these two tubes are conducting, the series transformer secondary is effectively short-circuited and the primary impedance is reduced to a minimum, thus permitting practically full current to flow in the welding circuit. When the tubes are not conducting, the series transformer secondary is open-circuited and the primary impedance is high. In this condition the current is limited to the exciting current of the transformer, a value which, for purposes of welding, may be considered as practically zero. By proper control of the thyratron grids, these tubes may be made to conduct when desired.

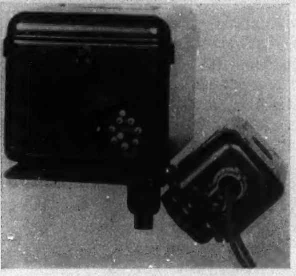

Fig. 3—Scanning Head for Photoelectric Paper Cutter Register Control

The grids of the power thyratron tubes are controlled by the thyratron synchronous timer, a system of smaller thyratron tubes. The thyratron synchronous timer consists of a timing circuit which, in the case of intermittent line welding machines, controls the time of the total welding cycle ("on" plus "off"), and a ratio-control circuit which controls the relation between the time "on" and time "off." The ratio-control circuit, the timing circuit, and the power control circuit all operate in synchronism with the system frequency and thus accurately maintain the time of the "on" period and the "off" period.

As the equivalent is used on spot welding machines, a small cam switch on the drive shaft controls the approximate starting time. The thryatron synchronous timer controls the actual starting time and also the length of the "on" period for the one spot weld.

The oscillogram in Fig. 1 show the accuracy and range of control. It will be noted that each "on" period corresponds exactly with each other "on" period for the same adjustment, even for "on" periods as short as one cycle.

A typical control panel is shown in Fig. 2. This particular panel may be used for either spot or line welding. The dials and switches for adjusting the timing are conveniently located on the front of the panel. The use of this equipment in connection with spot welding machines permits an accuracy hitherto unattainable. Used with intermittent line welding machines it permits, in addition to the accuracy of control, operation at speeds (*i. e.*, spots per minute) far in excess of those permissible with mechanical or magnetic circuit interrupting devices and of course the frequent replacing of contacts and mechanical parts is eliminated.

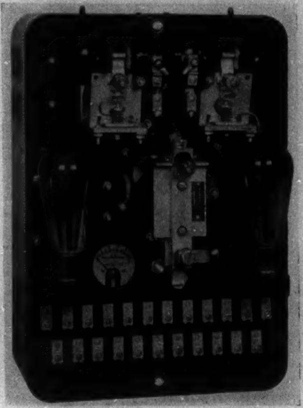

Fig. 4—Thyratron Panel for Photoelectric Paper Cutter Register Control

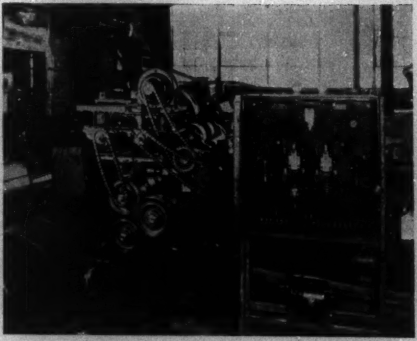

Fig. 5—Photoelectric Paper Register Control on Machine for Cutting Paper Bags

Mr. Gulliksen has presented a clear description of the operation of the photoelectric paper registry control system. We have found that in most applications, it is necessary to make a slight change of speed ratio between the cutter and draw rolls, as well as the position change. The speed ratio change is necessary to take care of the shrinkage and stretch of the paper and also because it is exceedingly difficult manually to adjust the speed ratio so that it is exactly correct. The position change brings the web back into registry and a relatively small speed ratio change tends to prevent it from getting out of register.

On those applications that require very high speed response, the time constant of the cable connecting the phototube to the amplifier becomes an important factor. When you consider that the time for response to a one-sixteenth inch spot traveling at 600 feet per minute is only about 1/2,000 second it is obvious that the interconductor capacitance of the phototube cable cannot be very much if the minute change in phototube current is to have any appreciable effect upon the grid voltage of the amplifier tube. To overcome this difficulty a "scanning head" has been developed, see Fig. 3. This is a small unit in which are mounted the phototube and its optical system, the amplifier tube, and the light source with its optical system. Thus the leads in the high impedance phototube-amplifier circuit are reduced to a few inches. This greatly reduces the time constant of the circuit and makes it possible to respond to impulses lasting only a few microseconds. The amplifier tube is connected to the thyratron panel by means of multiconductor cable. Since the amplifier anode circuit is of far less resistance than the grid circuit, interconductor capacitance in this cable has little effect upon the system. On the thyratron panel, illustrated in Fig. 4, are mounted the two thyratron tubes and the contactors which they control, and a time delay relay of the flux decay type.

The installation shown in Fig. 5 has been in service in the plant of the Jaite Paper Company, near Cleveland, since 1931. This is one of a number of installations on bag-making machines.

# The Use of Communication Facilities in Transmission Line Relaying

BY J. H. NEHER*

Associate, A.I.E.E.

***Synopsis.***—*This paper outlines the fundamentals of a method of obtaining overall protection of transmission lines by a comparison of the relative direction of fault current flow at the line ends by means of a communication system. The results obtained are equivalent to differential protection. The carrier-current pilot or d-c pilot wire schemes which have been introduced during the past few years are applications of this method.*

*The optional use of a communication system to link the trip circuits at the ends of a transmission line provided with any conventional form of relay protection is described. This insures the simultaneous tripping of both line ends for all fault positions.*

*The various types of communication systems adaptable for relay purposes are described and discussed in regard to coordination with the telephonic communication, telemetering or supervisory control systems employed as adjuncts of the power system.*

* * * * *

## INTRODUCTION

THE large size and complexity of the modern power system and the attendant problem of maintaining system stability at times of system faults have indicated the desirability and often the necessity of clearing faults on the major transmission lines of the system with the utmost rapidity. To meet this requirement high-speed circuit breakers and high-speed relays have been developed. The step-by-step distance relay has been evolved which permits the instantaneous clearing of faults over a greater portion of the line than was previously possible where balanced relays could not be used. The protection afforded by the selective timing relay schemes, however, even when reduced to a high-speed basis, falls short of the ideal in several important respects.

1. Faults at a line end, either in the case of a parallel line installation where balanced relays can be used, or in the case of a single-line installation where distance relays or the equivalent must be used, cannot produce instantaneous tripping at both line ends and sequential tripping at best must result at the station distant from the fault. In power systems comprising both steam and hydro generation, this necessary increase in the total clearing time may be sufficient to throw the hydro units out of step.
2. At the present state of the art, the distance relay is not entirely fool-proof when applied to protection against ground faults. Equivalent systems for determining distance on ground faults by measuring the residual current are not universally applicable.
3. In certain complicated systems it is difficult to make the step-by-step distance relays on one line section select with the relay equipment on adjacent sections without some sacrifices in the time of operation for faults in the section protected.

It is natural, therefore, that considerable interest should be shown in the development of systems of *overall protection* for transmission lines. This form of protection, which will trip both line ends instantaneously for all faults on the line, and which is non-operative for systems faults not on the line, and therefore inherently selective, represents very nearly the ideal relay system. Overall protection employing *differential* relays, *i.e., differential protection*, has been used to some extent for the protection of short transmission lines; but the cost and complication of providing a group of a-c secondary or *pilot* wires paralleling the transmission line with the attendant difficulties of maintaining these pilot wires, keeping them free from induced effects, and handling the high-current transformer burdens involved has prevented the widespread use of this method.

During the past few years overall protection has been successfully accomplished on a number of transmission lines throughout the country by the application of methods whereby the relative instantaneous directions of residual current, or the relative directions of fault current flow at each end of the line, are compared by a communication system which is arranged to trip both ends of the line when the relation obtained indicates that the line is faulted. These methods, while differing as to the details of the relay or the communication systems used may be given the title *directional comparison.* Overall protection by directional comparison using a communication system as the auxiliary link between the line terminals has advantages over differential protection because a reliable communication system can be provided more readily and at less expense than a-c pilot wires.

Communication facilities may also be employed as an adjunct to a selective timing relay system of any type to permit the simultaneous tripping of the breakers at both ends of the line upon the operation of the relay system at either end. This system, which may be termed *transferred tripping*, is useful in cases where selective timing relay systems may be employed to give instantaneous operation at one end of the line under all fault conditions; and where, due to stability considerations it is necessary to trip both line ends instantly without waiting for sequential or second zone operation at either end.

The communication facilities required for either of

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these protective schemes are those of a telegraph system. The medium employed may be the transmission line itself by means of carrier-current, or else telegraph or telephone circuits either owned by the power company or leased from a telephone company. The choice of the particular communication system to be used will depend upon a wide variety of local conditions and considerations. It is the purpose of this paper to discuss these various systems from the standpoint of their individual characteristics, and also to indicate the possibilities for the correlation of the relay communication system with the telephonic communication, telemetering, or supervisory control systems which may be simultaneously employed.

### PRINCIPLE OF OPERATION

*Overall Protection by Directional Comparison.* The underlying principle of operation of the *directional comparison* method of relay protection is based upon the fact that the presence or absence of a fault on a transmission line can be determined from a knowledge of the relative directions of power flow at each end of the line. As an example, consider the usual case of a transmission line running between two stations, each of which is connected to a generating source, and assume that this transmission line is provided at each end with a power directional relay arranged to close its contacts when power flows into the line at that end. With this arrangement it will be seen that under conditions of normal power transfer over the line in either direction, the contacts of the directional relay at the receiver end of the line will always be open. This same condition holds in the case of a through fault in either direction.

If a fault occurs on the line, however, the presence of generating capacity at both ends of the line will cause the flow of power at each end of the line to be towards the fault with the result that both directional relays will be closed. Conversely, it follows from what has been said that the simultaneous closure of both directional relays indicates that the line is at fault. If a system of communication is set up between the ends of the line whereby the fact that both directional relays are closed at the same time may be established and made known at each end of the line, we have the essential elements of a relay protective system which performs in exactly the same way as the conventional system of differential protection.

Of course this arrangement presupposes that the directional relay at each end of the line will always function as intended under every fault condition which may occur on the system regardless of the type or location of the fault. This requires that particular attention be paid to the design of the directional relay system used at each end of the line, but it is possible to design this equipment so that all conditions can be met, even when either end of the line protected may not always be connected to a generating source. In the case of tapped lines, it may be necessary to install a directional relay system at the end of the tap and to connect the communication system to this point as well.

It may be well to point out here that this relay system is not particularly well suited to the protection of a piece of equipment which may develop partial faults such as turn-to-turn faults in a generator, motor or transformer. It is desirable to clear such faults to prevent further damage to the equipment, and they can be cleared if the more sensitive types of differential protection are used. With the directional comparison system, it is impossible to do this because power flow would continue through the equipment and one of the directional relays would remain open.

A transmission line, on the other hand, cannot develop a fault between phase wires and continue to transfer power over the phase affected. While this may be possible in the case of a ground fault on a transmission line, this condition is cared for in the design of the directional relay system by the addition of a ground relay so that the system will function correctly on ground faults as well as phase faults.

The communication system, which is considered as including the mechanism whereby the relative indications of the two directional relays are compared and the tripping operations initiated as well as the actual medium of communication, may be considered as a telegraph system. In its simplest form it consists of a conventional d-c telegraph circuit between the ends of the transmission line in which the *keys* are actuated by the directional relays and the *sounders* are replaced by auxiliary relays arranged to trip the circuit breakers. This arrangement is shown in Fig. 1. This circuit automatically compares the relative directions of power flow at the ends of the line and initiates the tripping operations under proper conditions, since current can flow in the telegraph circuit and through the tripping relays only when both directional relays are closed at the same time.

In practise, the single directional relay shown is usually a directional relay system consisting of a group of relays designed to operate properly under all possible fault conditions. Furthermore, the system is so arranged that the *keys* are actuated only when there is a fault on the power system, so that under normal conditions the *keys* at both ends of the communication circuit are open irrespective of whether or not load is being carried over the line. Stated another way, the directional relay system is inherently a *fault detector* as well as a *directional detector*. This arrangement is necessary, as will be shown later, to secure the most reliable operation from the communication system.

There are several directional relay arrangements which are suitable for use with this protective scheme. In the case of protection against phase faults, a single directional relay of the polyphase type or else three single-phase units may be used. If the line is provided with directional phase or ground relays for back-up purposes in addition to the overall protection, the directional elements of these relays may be used to control the overall protection, provided the contacts of these directional elements are placed in the trip circuit of the relays as is often the case. When single-phase directional elements having true or approximate wattmeter characteristics are used, it is necessary to associate an instantaneous overcurrent relay installed in the same phase with each directional element. The contacts of the directional and overcurrent elements of each phase are connected in series and the three-phase groups connected in parallel. It is possible to have an unsymmetrical fault behind the group of directional elements of such a nature that one of the single-phase directional elements will reverse and close its contacts. The phase on which this can happen will be carrying a relatively small current, however, so that the introduction of the overcurrent element set at the proper value will prevent the group of directional elements from closing the control circuit of the protective scheme.

These overcurrent elements also prevent this control circuit from being closed at either end of the line due to the flow of load current, which is necessary for the proper operation of the scheme. When a polyphase directional relay is used, it must either be provided with voltage restraining coils which will hold the contacts open under load conditions or else be supplemented by a set of overcurrent elements to accomplish the same result.

Some single-phase directional elements are provided with voltage restraining coils so that their contacts are normally open under flow of load current and have operating characteristics such that the use of additional overcurrent elements are not necessary if they are used to control the protective scheme.

The directional elements of ground relays are normally open so that an overcurrent element is not strictly necessary, but the use of such an additional element may be considered desirable to reduce the sensitivity of the device.

It has been assumed so far that there is a source of fault current supply at each end of the line. The system can be made to function in case there is not a source of fault current supply at one end by replacing the directional relay at that end by an equivalent system such as an instantaneous overcurrent element and an instantaneous undervoltage element in each phase. The first element is circuit opening on overcurrent and the second element is circuit closing on undervoltage. The contacts of the two elements are connected in series. Normally the control circuit is open due to the presence of voltage on the transmission line, but if the phase under consideration is faulted the voltage will drop causing the voltage element contacts to close. If this condition is caused by a through fault, however, the current element contacts will open before the voltage element contacts can close so that the control circuit will not be closed. If the fault is on the line the current element contacts will not open, so that the control circuit will be closed as soon as the voltage element contacts have closed. A somewhat similar arrangement can be made to secure correct operation on ground faults.

Other possible arrangements suggest themselves. When there is sometimes but not always a source of fault current supply at either end of the line, it is necessary to use both a directional relay and the above combination of current and voltage elements or some equivalent arrangement.

Under certain conditions, the phase relay system may operate incorrectly at times of ground faults. When this can occur it is necessary to provide both a phase and a ground relay system and to interlock the two systems so as to render the phase relay system inoperative when there is flow of ground current.

*Transferred Tripping.* In this arrangement, the communication system is used as an adjunct to a standard relay protection scheme either of the balanced current or step-by-step distance type in order to insure instantaneous tripping of both ends of the line under all conditions of faults occurring on the line. It is assumed that the relay protective scheme is of such nature that instantaneous tripping may be secured at, at least one end of the line for any type or location of fault on the line. The communication system, arranged as shown in Fig. 2, merely serves to trip the other breaker as soon as either breaker trip coil is energized.

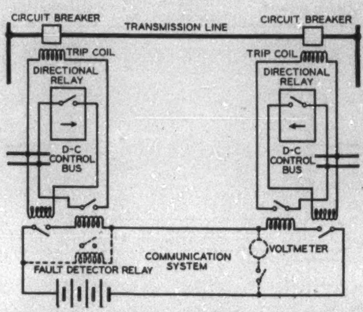

Fig. 1—Diagram Showing the Use of a Communication System to Obtain Overall Protection by Directional Comparison

While this method is similar to the directional comparison method in that instantaneous tripping for all fault positions on the line is obtained, its selectivity in the case of external faults depends upon the selectivity of the relay protection scheme at either line end. This relay protection scheme will be more complicated and costly than the directional relay system required by the directional comparison method. On the other hand, the line is completely protected, even if the communication system fails to operate. The directional comparison method will probably be the more desirable in the majority of cases, although transferred tripping may be useful in certain instances where selective timing relays are already installed or where there is an objection to the use of a communication system as a component part of the first line of defense. Either method requires a communication system of substantially the same form which must be as fast and as reliable in operation as possible.

## TYPES OF COMMUNICATION SYSTEMS

The types of communication systems which are adaptable to this service are the d-c telegraph, the low-frequency rectified a-c pulse telegraph, carrier-current, and the voice-frequency telegraph. These systems will be described as applied specifically to the directional comparison method only, but the modifications required to adapt them to transferred tripping are self-evident.

*D-C Telegraph.* The fundamental circuit of the d-c telegraph system has already been shown in Fig. 1. With this arrangement, however, it is evident that a short circuit on the telegraph line will cause the line to be tripped at the end at which the telegraph battery is located if the directional relay system at that end is closed, irrespective of the operation of the directional relay system at the other end. This would result in an incorrect operation in the case of a through fault on the power system. For this reason, it is necessary to provide the telegraph circuit with a monitoring system which will detect faults on this circuit and automatically render the relay system inoperative before a through fault is likely to occur. This can be done by normally energizing the telegraph circuit through the coil of a sensitive *fault detector* relay as shown in dotted lines in Fig. 1. This fault detector relay may be arranged to lock open the telegraph circuit and give an alarm.

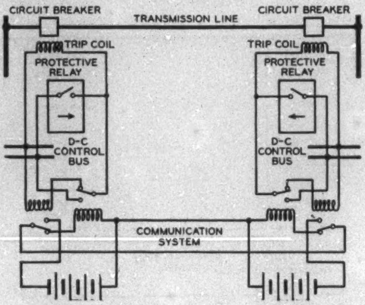

FIG. 2—DIAGRAM SHOWING THE USE OF A COMMUNICATION SYSTEM TO OBTAIN TRANSFERRED TRIPPING

Whenever a through fault occurs on the power system in such a position that the directional relay system at the end away from the battery will close, this will close the telegraph circuit through the fault detector relay. It is therefore necessary that the fault detector have sufficient resistance to keep the flow of current below the operating point of the tripping relay at the distant end; and since the fault detector relay will operate, it is necessary to introduce a time delay in the lockout feature so that such a system fault can be cleared before the telegraph circuit locks out.

The telegraph circuit can be checked for continuity at any time by introducing a high resistance voltmeter at the end away from the battery, as shown by the dotted lines in Fig. 1. It is possible to secure an automatic indication of continuity by substituting a sensitive undervoltage alarm relay for the voltmeter, but this relay must have a sensitivity greater than the fault detector relay and sufficient resistance to keep the normal flow of current below the operating point of the fault detector relay.

The conventional d-c telegraph circuit employs a single wire with ground return. While this arrangement is theoretically suitable for use in this connection provided the grounding points of the telegraph circuit are made at considerable distances from the power system grounds, it is not in general as safe or reliable for this particular service as the two-wire or metallic circuit grounded at only one point.

The details of equipment and circuit arrangement will vary to a great extent with local conditions. In general, it is desirable to incorporate as much of the equipment associated with the telegraph circuit as possible in a single case so that it may be treated as a unit similar to a power relay. Fig. 3 shows the relay assembly used by the Philadelphia Electric Company at the battery end of the circuit consisting of circuit closing, tripping, fault detector, lockout and oil dashpot relays, the latter being used to give a time delay to the lockout function. Fig. 4 shows the relay assembly used at the other end of the circuit comprising circuit closing and tripping relays, together with a voltmeter for checking the continuity of the circuit. This latter assembly was designed for a 10,000-volt insulation between the telegraph circuit and the station control circuits which is required for all telephone circuits entering the particular station in which this relay assembly is located.

At the present time, to the writer's knowledge, installations of over-all protection by directional comparison employing the d-c telegraph have been made by the Oklahoma Gas and Electric Company[1], the Duquesne Light Company, the Los Angeles Gas and Electric Corporation,[2] the Tennessee Electric Power Company, and the Philadelphia Electric Company. The last four of these companies employ a two-wire metallic circuit either owned by the power company or leased from the local telephone company for each transmission line protected. The Oklahoma installation employs a grounded telegraph circuit derived from a simplexed telephone circuit which is also used for telephone conversation between the stations at the line terminals.

*Low-Frequency Rectified A-C Pulse Telegraph.* In general, two d-c telegraph circuits would be required for the protection of two parallel transmission lines. Although various modifications employing polarized relays and additional batteries may be made which permit the use of a single telegraph circuit, these arrangements are complicated and will not operate if both transmission lines are simultaneously faulted. In order to overcome these difficulties the arrangement shown in Fig. 5 is suggested, employing an alternating electromotive force of low frequency and suitable rectifying units acting as valves to control the flow of current through the tripping relays. The telegraph equipment of the upper line is operated by the positive half cycles of the voltage furnished by the alternator, while the equipment of the lower line is controlled by the negative half cycles. The use of low frequency is desirable to minimize the line reactance. The tripping relays must be designed to hold in over the opposite half cycles during which they receive no current. A standard 20-cycle ringing machine, continuously driven by a d-c motor from the station control battery would serve as the alternator, and standard copper-oxide rectifying units are suitable for use as valves. A d-c monitoring system may be readily adapted to the circuit.

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[1] For references see bibliography.

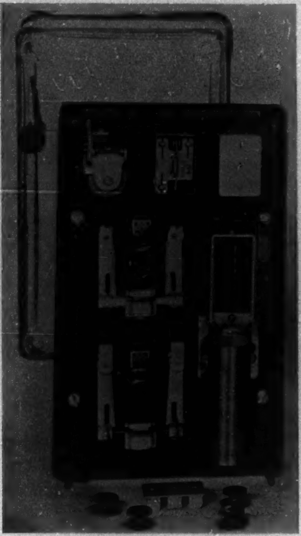

Fig. 3—D-C Telegraph Relay Assembly for Battery Station

This is a pulse system and must not be confused with an alternating current system. Care must be taken to prevent the current pulses from setting up counter electromotive forces in the circuit and for this reason transformers cannot be used as coupling or line insulating devices.

*Carrier-Current.* A carrier-current system of overall protection of transmission lines against ground faults has been in operation on the Southern California Edison System for several years.[3] In the manufacturer's original design of carrier-current protection, the relative instantaneous directions of the residual current at each end of the line were compared by means of the carrier-current equipment,[4] rather than the relative directions of residual current flow. This arrangement had several disadvantages, including the limitation that while protection could be secured against either phase faults, or ground faults, it could not be secured against both types of faults simultaneously with the same equipment. As a result the present form of this equipment offered by the manufacturer is based upon directional comparison of fault current flow and is therefore applicable to protection against all types of faults.[5,6]

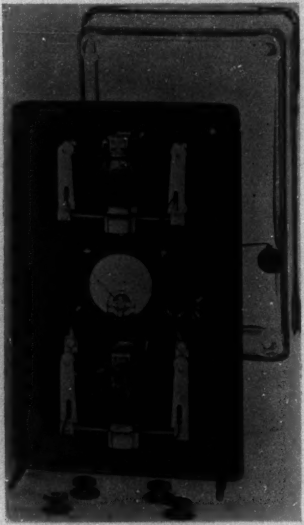

Fig. 4—D-C Telegraph Relay Assembly for Distant Station

The general arrangement of this equipment is indicated in Fig. 6. The line is equipped at each end with a carrier-current transmitter consisting of a vacuum tube master oscillator and power amplifier and a simple single tube receiver suitably coupled to two conductors of the transmission line. Since the transmission line is used as the communication channel, a short circuit between the conductors forming this channel would render the communication system inoperative. It is therefore necessary to arrange the equipment so that the signals transmitted are used to prevent, rather than to initiate, the tripping operations. This in turn requires the installation of traps in the transmission line to prevent external faults from interfering with the communication. The signal transmission at each end of the line is initiated by an instantaneous directional relay (transmitter starting relay) which is directional towards the bus. The back contacts of this relay on opening put the master oscillator of the transmitter into operation. A second directional relay (tripping relay) which has a slight time delay and is made directional towards the line initiates the tripping operation unless a signal is received before its contacts have closed. If there is a fault on the line, therefore, no signals will be transmitted or received and the tripping operations are allowed to take place. In the case of a through fault, the tripping directional relay starts to operate at the end where power is flowing into the line, but a signal is instantly transmitted from the other end, and is received in time to open the trip circuit before the contacts of the tripping directional relay have closed.

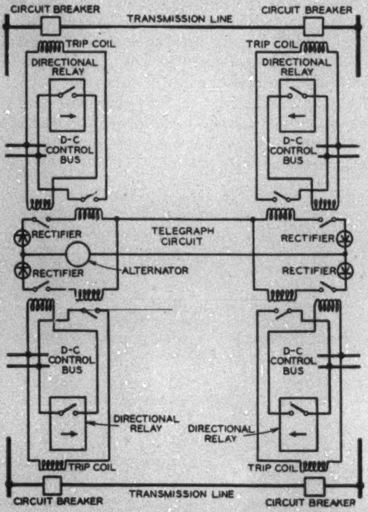
CIRCUIT BREAKER
TRANSMISSION LINE
CIRCUIT BREAKER
TRIP COIL
TRIP COIL
DIRECTIONAL RELAY
DIRECTIONAL RELAY
D-C CONTROL BUS
D-C CONTROL BUS
RECTIFIER
TELEGRAPH CIRCUIT
RECTIFIER
RECTIFIER
ALTERNATOR
RECTIFIER
D-C CONTROL BUS
D-C CONTROL BUS
DIRECTIONAL RELAY
DIRECTIONAL RELAY
TRIP COIL
TRIP COIL
CIRCUIT BREAKER
TRANSMISSION LINE
CIRCUIT BREAKER

Fig. 5—Low Frequency Rectified A-C Pulse Communication System for the Protection of Two Transmission Lines

A single frequency (100,000 cycles) is used for transmission in both directions and the transmitters and receivers are tuned to this frequency. The filaments of the vacuum tubes are kept energized continuously, and the slight time delay required in initiating the tripping operation can be made as low as 3½ cycles with assurances of getting positive lockout on through faults.

Since the failure of either a transmitter or receiver equipment can produce tripping in the case of a through fault, some means of automatic supervision is necessary. This takes the form of a periodic timing device at each line end that momentarily energizes the transmitter. The associated receiver, being tuned to the same frequency, should respond and operate the receiver relay. The device is so arranged that an alarm is given in case the receiver fails to operate. By proper synchronization and arrangement of the supervising devices at the line ends, it is possible to check the overall transmission between stations and automatically to lock open the trip circuit at either end in case a signal is not received from the other end at the appointed time.

*Voice-Frequency Telegraph.* A system of voice-frequency telegraphic communication suitable for the transmission of twelve messages simultaneously over a telephone circuit is in use by the American Telephone and Telegraph Company.[7] This system operates on the principle that a different frequency is used for each telegraph channel. The twelve frequencies are superimposed on the telephone circuit and separated at the receiving end by band pass filters after which each frequency is rectified and permitted to operate a receiving telegraph relay.

This system may be readily adapted for relay communication as shown in Fig. 7. When the directional relay at either end of the transmission line closes, it permits the voice-frequency transmitter associated with it to transmit a signal of a definite frequency over the telephone line. The receiver system at the other end of the transmission line is tuned to respond to this frequency and to this frequency only. The system is arranged to trip the line when a signal is received at either end at the same time that the directional relay at that end is closed. The transmitter at one end of the line must be prevented from operating the receiver at the same end; this may be done by using two frequencies for each transmission line or else by substituting a *bridge transformer* for the repeating coil shown on the diagram. Such arrangements will keep the transmitted

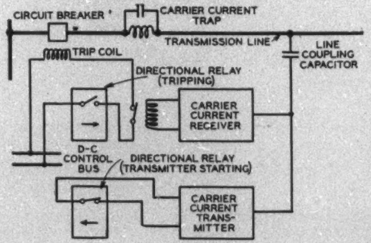
CIRCUIT BREAKER
CARRIER CURRENT TRAP
TRANSMISSION LINE
LINE COUPLING CAPACITOR
TRIP COIL
DIRECTIONAL RELAY (TRIPPING)
CARRIER CURRENT RECEIVER
D-C CONTROL BUS
DIRECTIONAL RELAY (TRANSMITTER STARTING)
CARRIER CURRENT TRANS-MITTER

Fig. 6—Arrangement of Carrier-Current Communication System

frequency out of the receiver, so that both transmitters associated with one transmission line can operate at the same frequency thus permitting the protection of twelve transmission lines with a single telephone circuit.

A suggested design of the voice-frequency telegraph equipment incorporating the transmitter and receiver in a single unit operative from a 250-volt power station control battery is shown in Fig. 8. The filaments of the vacuum tubes are continuously energized and the equipment is put into operation by the directional relay which applies plate potential to the tubes.

## SELECTION AND COORDINATION OF COMMUNICATION SYSTEMS

The selection of the type of communication system best suited for the protection of a given transmission line involves a great number of considerations, many of which are beyond the scope of this paper. In general the type of relay communication employed should be closely coordinated with the type of telephonic communication used between the power stations involved. For instance, if the transmission line is equipped with a carrier-current telephone, the natural choice of relay communication would be the carrier-current type utilizing the existing coupling devices which represent a major part of the cost of this system. And where telephone circuits, whether leased or privately owned, are the most economical means of telephonic communication, the relay communication should utilize, if possible, the same or similar circuits.

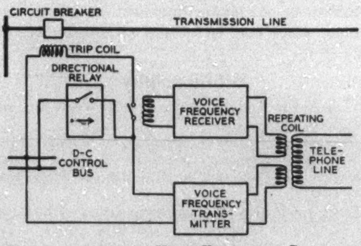

FIG. 7—ARRANGEMENT OF VOICE-FREQUENCY COMMUNICATION SYSTEM

In comparing the carrier-current system with the systems employing telegraph or telephone circuits, an important difference should be noted which arises from the use of the transmitted signal to prevent rather than to initiate tripping. In the case of the carrier-current system, failure of the communication equipment will not interfere with the tripping of either end of the line for faults on the line, but may result in the tripping of a line end on through faults in one direction, depending upon what part of the communication equipment fails. Substantially the reverse is true with the other systems, since the failure of the communicative equipment renders the protective system inoperative. Where suitable backup protection can be provided, it is generally more desirable to have equipment failure render the primary protection inoperative than to have it make the system susceptable to inselective operation. However, many exceptions to this principle will be found. With proper supervision of the equipment, the probability of experiencing serious system trouble as the result of the failure of either system is extremely small.

There is little choice between systems in respect to their speed of operation. The operating time of the carrier-current system has been given as 3½ cycles, but this time can probably be reduced slightly where it is necessary. Contrasted with this, we have the sum of the operating times of a directional relay and a tripping relay which determines the operating time of the other systems. This time cannot be made materially less than 1½ cycles. With the high-speed breakers available at present having operating times in the order of 8 cycles, the difference in operating times of the communication systems is negligible.

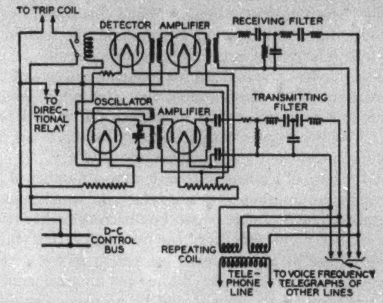

FIG. 8—DETAILS OF VOICE-FREQUENCY TELEGRAPH COMMUNICATION EQUIPMENT

The carrier-current system is not adaptable to the protection of cable lines due to the fact that the cable capacity furnishes an effective short circuit across the line and thus prevents the passage of the signals.

Where telegraph or telephone circuits are used, these circuits will, in the majority of cases, be leased from the local telephone company. In this event, certain restrictions are placed on the circuits as to the magnitude of the voltage applied and current circulated; and also, in certain cases, a high degree of insulation strength will be required between the communication circuit and the power station ground or control circuits.[8] These conditions may be complied with by the suitable design of the communication equipment in the power stations.

In order to prevent interference with these circuits in the telephone exchanges through which they pass, special tagging may be employed, such as has become the custom with radio broadcasting circuits. The use of monitoring devices will indicate at once the occurrence of trouble on the circuit and the modern telephone plant is so equipped that most trouble can be rectified in a very short time after it has been brought to the attention of the telephone company.

The d-c telegraph is the simplest and probably the most reliable form of relay communication, but as it requires a separate circuit for each transmission line protected, the cost of leasing these circuits may become an insurmountable item. The low-frequency rectified a-c pulse telegraph permits the protection of two transmission lines between the same power stations with a single communication circuit. While this system is in the experimental stage and will probably be limited to use with relatively short communication circuits, nevertheless it offers possibilities for reducing the cost of the protection. The disadvantage that the failure of the communication circuit will invalidate the overall protection of two lines is not particularly serious if the circuit has a sufficiently high degree of reliability.

In the case of a power system having a number of interconnected stations within a relatively small area, a single telephone circuit might be run from each station to a central point, and all of the interconnecting transmission lines be given overall protection by use of the voice-frequency telegraph. While such an arrangement has not been tried, there should be no particular difficulty in constructing voice-frequency telegraph units along the general lines indicated in Fig. 8, which would be comparable in cost and reliability to the higher frequency units utilized with the carrier-current system. Under such conditions, the cost of carrying the few telephone circuits required might be considerably less than the investment in transmission line coupling devices and traps required by a complete carrier-current installation.

When the power stations terminating the transmission line are directly connected by one or more telephone circuits, it is often possible to superpose either the d-c or low-frequency rectified a-c pulse telegraph on such telephone circuits. Such superposition is accomplished by simplexing or compositing.[8] With respect to circuit facilities leased from telephone companies, it is the practise of certain of these companies to charge for their facilities on a channel basis. Where a talking channel and a superposed telegraph channel are both provided, the charge for each channel would be applied.

When telemetering or supervisory control is used between the power stations it may be possible to use the same circuits for relay communication as well, providing the two systems can be properly coordinated.

Undoubtedly, there are other communication systems or arrangements suitable for relay purposes which have not been mentioned, but the systems which have been discussed appear to be the most readily adaptable. In the final analysis the communication system is the heart of the protective schemes described. Communication is an art somewhat apart from relay engineering, and it is hoped that the few principles contained in this paper may be of some interest to those more familiar with this art in providing facilities suitable for relay purposes.

## CONCLUSIONS

The following conclusions may be drawn from the foregoing discussion:

1. Overall protection of transmission lines may be accomplished by comparing the relative directions of fault current flow at the terminals of the line. This arrangement resolves into a directional relay system at each end of the line interconnected by a communication system.
2. Directional comparison secures all the advantages of differential protection; and by substituting a communication system for a-c pilot wires, results in a simpler, more reliable and less costly installation.
3. The directional relay system required utilizes standard relays which in certain cases may be component parts of the normal or backup protection of the line.
4. A communication system can also be used to link the trip circuits at the ends of a transmission line provided with any conventional protection, thus insuring the simultaneous tripping of both line ends for all fault positions.
5. Several types of communication systems are readily adaptable for relay purposes. The choice of the particular system to be used is governed by local considerations, particularly in regard to possible coordination with other telephonic, telemetering, or supervisory control circuits employed as adjuncts of the power system.
6. The relay communication system is the heart of the protective scheme. The widespread use of transmission line protection by the methods outlined lies in the availability of communication facilities which are reliable and which may be secured without undue cost.

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## Discussion

**E. E. George and W. R. Brownlee:** Mr. Neher's paper has brought out a number of significant facts regarding pilot wire relaying and it should also arouse a great deal of renewed interest in system protection by this method. In the light of our limited experience and study we are in accord with practically all of his conclusions.

The Tennessee Electric Power Company has in operation a 14-mile 110-kv overhead transmission tie line protected by a 7-mile loop of metallic telephone circuit. Full back-up protection has been provided. This pilot wire installation was completed on November 20, 1932, at which time a series of short-circuit tests involving arcs both phase-to-phase and phase-to-ground was made. The results of these tests showed that very rapid and accurate protection was secured by means of pilot wire protection. None of the difficulties which were formerly experienced in connection with induced currents or voltages was encountered. However, it was found that the pilot wire itself would draw enough charging current when the contacts at one end only were closed to cause the tripping relays to operate occasionally. This was corrected by means of connecting a 2-$\mu$f condenser across the coil of each tripping relay. The few system operations since this time have been correct in that the pilot wire protection has cleared all faults within this section very rapidly and has not operated in cases of through trouble. The d-c telegraph system was preferred on account of its simplicity and reliability particularly since we much prefer that a relay equipment failure should result in a circuit failing to trip when desired instead of causing various circuits to open incorrectly. The metallic telephone circuit is leased from the Southern Bell Telephone and Telegraph Company.

*Insulation.* For the auxiliary circuit closing relays and tripping relays this company uses a small relay provided with a vacuum contact in order to secure the required insulation between the telegraph circuit and the station circuits. Also the operating battery is leased from the American Telephone and Telegraph Company and is located at its exchange since it was necessary that both ends of the circuit should have high insulation. Even in cases where high insulation is not required at both ends it is desirable to compare the cost of dry batteries with the rental charge of a storage battery at the exchange. The relative economy may depend on the load taken from the battery for supervisory purposes.

*Direction.* It has been found very advantageous to use 3 single-phase directional units with voltage restraint and with torque depending on phase angle for phase protection. This avoids the complication of additional overcurrent relays and the necessity of locking out the phase relays on the occurrence of ground faults. Potential amplification permits high speed at low voltages. In order to obtain the desired speed and sensitivity in case of single-phase faults to ground we prefer to add a high speed directional ground relay with its contacts in parallel with the phase relays.

*Line Tests.* When an overhead line has been cleared at both ends by relay protection it is customary to make a test on this line at full voltage from one end or the other. The usual scheme of pilot wire protection would be out of service for such a condition. Even if a combination of under voltage and current relays as described for use at stations where there is no power supply were added to each end of the line, correct operation could not be secured unless the potential transformers were on the line side of the oil circuit breaker.

We are considering the use of an auxiliary finger on the oil circuit breaker which is closed when the oil circuit breaker is open to be connected in parallel with the directional contacts at each station. Of course an insulating relay must be interposed if high insulation is required. If it is found impractical to coordinate the auxiliary fingers on the oil circuit breaker so that the *b* finger opens sufficiently ahead of the closing of the *a* finger (in series with trip coil) when the breaker is closed, the circuit of the *b* finger may be placed in series with a contact on the control switch which is open only during the time the control switch is being operated.

*Supervision.* An open circuit in the pilot wire or a battery failure can be detected readily with volt meters or possibly alarm relays whether the battery is located at one end or at the center of the loop. This company is experimenting with the use of neon lamps for this purpose on account of the fact that they can be noticed much more readily than volt meters. With good supervision it is likely that a short circuit on the pilot wire circuit would be detected and the pilot wire equipment removed from service before a short circuit would occur on the high tension system.

**G. B. Dodds:** It may be of interest to state that the use of communication facilities for transmission line relaying has not been confined to this country, but has also been used in both England and Australia. In the December 1932 issue of an English publication, the *Metropolitan-Vickers Gazette*, is an article on "D-C Pilot Wire System of Relay Protection" by C. M. Longfield and A. D. Stevenson. In this article reference is made to an installation made in Sidney, Australia, in 1929, which has been in successful operation since that time. Additional reference also is made to this type of protection in the *Bulletin of Institution of Engineers*, Australia, Volume 5, No. 20, October 1928; and also in a paper on "Recent Developments in the Protection of Three-Phase Transmission Lines and Feeders" by Messrs. Ross and Bell, *Journal of the I.E.E.*, July 1930.

It is significant that in England, where various forms of a-c pilot wire protection have been used extensively and considered to give the most reliable and satisfactory protection (where its cost was not prohibitive), they are considering the use of this new principle of protection.

It is also of interest to note that in the systems described in English literature, a majority of them operate on what is termed the "lock-in" principle, that is, considering a ring feed, in which a number of automatic breakers are in series, only the breaker closest to the fault would be permitted to trip, while the other breakers were locked-in by having their trip circuits opened by the initiation of the relay closest to the fault. This is similar in principle to the operation of the carrier-current protection referred to in Mr. Neher's paper.

This new type of protection will serve as a valuable adjunct to the protection methods now in use. It will permit the solution of many difficult protection problems which otherwise could not be solved except by a more expensive means. However, it will not supplant the many established forms of protection now in use, but will rather supplement them as an accessory tool. It is not believed that the older forms of a-c pilot wire will be altogether superseded as it is still felt that, particularly on short transmission loops, the old type of pilot wire protection will cost no more and will have some advantages—one of which is that no potential transformers are necessary.

**A. F. Rose:** In dealing with the selection of communication systems the author mentions that an important distinction between power line carrier channels and other types of circuits which do not depend on power line continuity, is the use of the transmitted signal in the first case to *prevent* breaker tripping, whereas with the isolated communication channel the signals are used to *initiate* tripping. Where a power line carrier system is used, there are obvious reasons favoring the use of the former type of tripping control whereas with an isolated communication channel which is dependable, the choice between the two types of tripping control need not be biased by the communication channel limitations. Also, the isolated communication channel permits changing from one type of tripping to the other in the event changes in the power network make this desirable in addition to permitting the initiative method which the author generally prefers. The use of isolated communication channels, therefore, seems generally most desirable.

The author also mentions the restrictions on voltage and current which are involved in cases where the circuits are leased from the Telephone Company and that these requirements do not ordinarily limit the practical operation of the overall protection system. In some cases, however, the types of terminal apparatus may cause sufficient wave form distortion of the voltage or current in the leased circuit to react unfavorably on other nearby communication circuits. As pointed out in the report of the Subcommittee on Telemetering, Supervisory Control, and Associated Communication Circuits presented at the Cleveland meeting last year, most of the manufacturers plan their equipment so as to avoid this reaction. In cases where this has not been done by the manufacturer the extent of the reaction can be easily determined by test and, where necessary, corrective devices readily applied.

**E. H. Bancker:** Mr. Neher's paper is very opportune because it is becoming more and more apparent that it is difficult if not impossible for relays using factors available at one point of a system to provide the speed and selectivity desired and also to distinguish between fault and subsequent oscillation conditions.

The three electrical dimensions of an alternating-current system are voltage, current, and the angle between them. These three and time, are the only quantities available at any point whereby relays situated there may attempt to determine that there is a fault and ascertain its whereabouts. Almost every conceivable combination and permutation of these quantities, products, differences, and quotients, has been employed singly and in groups, and the result is an ever rising standard of performance that, as pointed out by Mr. Neher, is still somewhat removed from the ideal.

In view of the many ingenious ways in which current, voltage, angle, and time have been combined there would seem to be rather faint hope that any further combinations will greatly improve the performance of relays dependent upon them. The solution appears to be to go elsewhere on the system for further analytical data and to what more obvious place than the other end of the circuit in question? The familiar differential and pilot methods of protection used this principle by bringing together for comparison the magnitude and/or phase angle of the terminal currents.

There are both technical and economic limits to the distance over which such information may be transmitted but if some form of comparison, such as power direction, can be made locally and the result translated into contact position, any reliable telegraph channel is suitable for conveying information from one end of a circuit to the other. This is the important thing to be borne in mind because, although communication and protective relay arts have scarcely impinged on each other heretofore, both are highly developed and the protection engineer should not feel that he is venturing on untrodden paths in considering the use of a simple communication system to augment an almost standard group of relays.

The principles employed are so fundamentally sound and simple and the necessary devices of so nearly standard construction that the next few years should witness widespread acceptance of the idea of bringing communication facilities into protective practise. If this prophecy is fulfilled there will result not only faster clearing of faults but also a new freedom for the system designer and operator. The restriction to parallel operation of lines imposed by balanced relays will no longer apply if there are any reasons for doing otherwise. For example pairs of lines which are now tapped to serve some intermediate load areas may be rearranged as a series of loops. Faults will be cleared more rapidly and each station will have a feed from both directions with no increase in the number of breakers. Thus in the event of double-circuit faults, service still will be maintained. Lines of more than two ends are as easily protected as simple lines if the communication channel is available. Ground faults receive as good protection as those involving two or more wires, a feature that may not be required from stability considerations but one which is highly desirable nevertheless. Twin-circuit faults of any nature should clear as rapidly as single-circuit faults. This may become of increasing importance, because as efforts are made to render circuits immune to lightning, many single-circuit outages will be avoided but the remaining disturbances probably will increase the percentage (not number) of double-circuit faults.

Although much more could be said the foregoing is sufficient to indicate that there are many benefits to be derived from changes in relay practise, such as are outlined in Mr. Neher's paper. Believing this to be the case the General Electric Company has been active in the development of a carrier pilot protective system in which the carrier current equipment is assigned the simple task of indicating at one or more stations the position of power directional relay contacts at some other station. The articles mentioned in Mr. Neher's bibliography describe the system and tests made upon it.

Carrier has been selected as the most desirable medium of communication because as used, the channel must be reliable when it is wanted which is during external faults. If the line itself is not capable of serving as a communication channel, it is either because it is faulted or open-circuited. In the former case it is not needed as a communication link because the carrier is not sent out during internal faults. In the latter case there is no current to operate the tripping relays, so it is immaterial whether the channel is intact or not. It is recognized that although other communication facilities might serve to convey the required impulse, a transmission line carrying current to a fault elsewhere provides a self-checking channel of the greatest reliability. Therefore, unless alternative means effect a considerable saving, or there are technical obstacles to its use, it is believed that carrier is the most satisfactory of the communication channels avilable for pilot relaying.

**H. P. Sleeper:** Mr. Neher has made a very important point that attention should be given to the matter of the overall protection of transmission lines. Many of the ordinary relay systems in use today will disconnect one end of a transmission line rapidly but require a considerable time delay to effect the disconnection at the other end. Hence the simultaneous operation of the relays may be considered just as important as the factor of instantaneous disconnection.

Reviewing existing schemes of relaying, and interpreting this restriction literally, this narrows down our field to some type of differential protection. Of these pilot wire protection is the simplest. Formerly such protection made use solely of the a-c circuits and resulted in engineering problems of considerable magnitude.

Mr. Neher's paper describes a very ingenious method of overcoming such difficulties by effecting the differential action with the d-c control circuits only. This unquestionably is a distinct step forward in the art of differential protection. It has, however, the economic disadvantage of high cost, which is common to all schemes which use pilot wires of any type. This factor must be given serious consideration and may be prohibitive unless the engineering features of the scheme can be very highly capitalized.

There are substitutes for pilot wire protection, or overall differential protection to use a general term, in the nature of balanced protection between pairs of lines if available, and the use of schemes of current measurement, which, particularly in the case of ground protection, may be found to give instantaneous, simultaneous, or sequential operation of the relays on the ends of the lines. These schemes frequently offer an economic substitute for the more expensive pilot wire protection and offer only slight engineering disadvantages in comparison.

It is important to note, however, that none of these schemes offers a universal solution which can generally be applied to the protection of transmission lines in a complicated network. The scheme is yet to be developed which can be applied in all locations, which preferably cover both phase and ground protection of such lines, and which will economically meet all the requirements of ideal relaying. While all schemes of pilot wire relaying may fulfill the engineering specifications, the cost would rule out their common application. It is therefore important to note that while such schemes have been improved and simplified, as described in Mr. Neher's paper, they must continue to remain limited in their volume of applications for the reasons noted above. The panacea for the bulk of the relay engineer's problems is still undiscovered.

However the ills of time element relaying have been cured mostly by the use of relays of the distance type, as far as short-circuit protection is concerned. Ground distance relays are still unsatisfactory but progress is being made. It therefore seems quite possible that the ideal protective system which will operate on all ends instantaneously and simultaneously, for all types of faults, may be soon made available by combining relays of the distance type with some of the schemes described in Mr. Neher's paper, probably making use of the carrier current feature to avoid the disadvantage of pilot wires.

**C. A. Muller:** On modern power transmission systems the fast clearing of line faults is necessary so as not to upset the stability of the systems and further, to prevent prolonged voltage surges which cause customers' motors to drop off the line. The present schemes of high speed relaying, such as instantaneous overcurrent relays, definitely set to clear faults within a predetermined distance from the outgoing bus, balanced line relays, and distance relays of both the reactance and impedance types are each more or less limited in obtaining fast relaying under all conditions. It has been our experience that probably the most serious disadvantage of any of the above schemes is that they do not permit fast relaying when simultaneous trouble occurs on both circuits of a double-circuit line.

It has been apparent for a long time that the only method for accomplishing high speed clearing of faults 100 per cent of the times would be a relay scheme which would be equivalent to differential protection of the line section. During 1927-1928 we made a great number of field tests on a carrier current pilot system of relay protection to determine if the scheme was foolproof. Our experience with carrier current was such that we were satisfied that if the scheme could be made to operate satisfactorily it would give ideal protection. Although this original installation proved on field tests to have some serious defects, the results of these tests convinced us that the principle of employing carrier current in place of pilot wires was sound. After further study of this scheme of protection we became convinced that the only method to make it operate successfully was to employ carrier current solely for transmitting a signal from one station to the other station and to employ power directional relays at each station to determine whether the fault was internal or external to the section. Then, depending on whether the fault was external or internal, the directional relays would cause carrier current to be transmitted so as to block or not block the tripping relays as the case might be.

The outgrowth of this was the development of a very much simplified form of carrier current pilot system utilizing directional relays for actuation of carrier current and causing locking out of the tripping relays on through faults. An experimental installation of this type was made in Ohio on the Newark-Crooksville 66-kv line and field tests were made on it. The results of these tests[1] prove that this form of protection is reliable and can be depended upon to give satisfactory operation in a maximum time of four cycles.

Mr. Neher's paper presents very clearly the various other means in addition to carrier current that could be employed in place of pilot wires to obtain inherently 100 per cent protection of a line section with high speed relaying. In all of these schemes it is to be noted that power directional relays are employed at both stations to determine whether the fault is internal or external to the section and that the directional relays cause a signal to be transmitted from one station to the other station either to block or not block the tripping relays, depending on whether the fault is internal or external to the line section.

In regard to the employment of telephone circuits either leased or privately owned for pilot wires, it has been the experience on our system that the carrier current equipment is far more reliable than either leased or privately owned telephone circuits have been and that carrier current on a well-built transmission line could be depended upon to transmit a signal where all other means of transmission had failed.

**R. J. Wensley:** The application of protective relay systems should be studied rather carefully to ensure the selection of that system which will give the needed protection for the least cost. Due regard must be had for the importance of the service and the amount which can be spent for insurance of that service. Increased total loading limits due to improved stability is to be considered on the credit side of the evaluation when such increase in capacity is made possible by the increase in speed and certainty of selection of the relay system being considered.

The simplicity and high degree of reliability to be obtained by the use of leased pilot wires makes this form of high speed protection very desirable. The communication companies have made great strides in the perfection of their circuits, and a very high order of continuity is now available in the more thickly populated portions of the country. For short lines where leased pilot wires through "all cable" routes are available, it would seem probable that no other form of high speed protection would be as simple and as low in overall cost. As the lines increase in length, the annual rental cost rises in proportion and becomes uneconomical. Although conditions and cost vary with locality, voltage of line and other variables, it is probable that the limit of economical use of pilot wires will lie between 50 and 75 miles.

As a substitute for the leased pilot wires, there are three optional systems:

1. Specially built pilot wires.
2. Distance relays.
3. Carrier pilot system.

The first of these is almost obviously limited to cable systems within very short distances, usually inside the limits of a large city.

The second option has received much attention in recent years and much development work has been done to improve the speed and selectivity of such systems. It is possible to secure practically 100 per cent high speed protection for about 80 per cent of the transmission line and slightly delayed but fully selective protection over the remaining 20 per cent of the line. If the line is important and is loaded to such an extent as to approach instability, this 20 per cent portion cannot be tolerated.

The third option, carrier pilot systems, offers the only method by which long, important sections of line can be given fully selective, high speed relaying at a reasonable expense. There are many disadvantages which must be considered when carrier applications are discussed. None of these should be considered as bars to the use of carrier where such use is economically justified. But those making carrier applications should understand the limitations and the uncertainties of carrier operation.

Carrier systems require some form of coupling to the line. This grows increasingly expensive as the voltage of the line increases. Space must be provided in the substation structure for the coupling equipment. Series tuned chokes must be installed in the high tension lines to limit the carrier to a given section. Radio tubes of considerable capacity must be maintained in an energized condition at all times to be ready for instant service when needed. The resonant circuits of the receiver are liable to shock excitation which may be furnished by arcing grounds.

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[1] "Carrier Current Relaying Proves Its Effectiveness," P. Sporn and C. A. Muller, *Electrical World*, September 10, 1932.

In spite of all these disadvantages, there is a definite place for carrier pilot systems and the above cautions are intended only as a warning to prospective users of carrier that there are many difficulties to be surmounted, and that the equipment should be applied with its limitations fully understood.

In any event, the transmission line should be fully protected by an adequate system of relays to obtain the best possible selectivity, should the carrier fail to perform. Should the application be properly made, the carrier will serve as an added feature to ensure high speed but which will not paralyze the system should it fail. There are many transmission links where the service is of such prime importance that the added cost of the carrier pilot is well justified. A few cycles may often be the margin between no interruption to service and a very messy interruption with plants out of synchronism and much service impaired.

**J. H. Neher:** The use of a battery located at approximately the middle of the direct current telegraph circuit, as mentioned by Messrs. George and Brownlee, is ideal in many respects, and permits automatic fault detection and lockout at the power stations if the minimum operating current of the tripping relays can be made sufficiently above the operating current of the fault detector relays, which would be arranged to close their contacts when the normal current through the loop departed in either direction from the prescribed limits. In order to make the direct current telegraph as insensitive as possible to surges, stray currents, etc., it is desirable to make the tripping current as high as is permissible, and to use enough battery voltage (within the permissible limits) to drive this current through the loop. In certain cases it may not be possible to obtain the requisite battery facilities in the telephone plant to work the tripping current up to its permissible limit.

With regard to methods for making the protective scheme operative in case one end of a faulted line is closed back on the bus, the simplest arrangement consists of an additional connection between the contacts of the directional relay and the trip circuit through a set of contacts on the breaker closing control button. As long as this button is held in the closing position, the line is automatically given instantaneous relay protection.

In connection with the use of direct current pilot wires in England, protection by this means was suggested to the British Institute as early as 1908. The method was similar to the direct-current pilot wire loop which has been described; although British development seems to have been along the lines of the "lock-in" or "interlock" systems, using the transmitted signal to prevent the tripping operations, as Mr. Dodds points out. A recent development termed "duplex" trips either end upon the simultaneous closure of the directional relay at that end, and the receipt of a signal from the opposite end, a duplex telegraph circuit being employed to permit the simultaneous transmission of two signals in opposite directions. It is not apparent that this arrangement has any advantage over the direct-current pilot wire loop, since both systems are susceptible to incorrect operation in case of a short circuit of the pilot wire.

As Mr. Rose has stated, the use of an isolated communication system permits the use of the transmitted impulse either to initiate or to prevent tripping. In the case of carrier current the signal must be used to prevent tripping for reasons which have already been explained. Sufficient space was not available in the paper to discuss various possible modifications of the direct-current circuit and it may be well to note here that by making this circuit either of the open or closed type it is possible to arrange either the initiative or preventive methods so that the system will give either, positive operation for faults on the line protected (whether or not the pilot wire circuit is in trouble) at the expense of possible operations on through faults; or positive non-operation on through faults at the expense of possible non-operation for faults on the line. Where it can be used, the initiative method is desirable since it eliminates the necessity for time delay relays. The arrangement to be used is a matter governed largely by the particular installation and involves such factors as the efficiency of the back-up protection provided and the primary purpose for which the protection is installed. That is, if the overall protection is installed merely to speed up the clearing of an otherwise selective system, the arrangement giving positive non-operation on through faults is to be preferred; whereas if the overall protection is installed to obtain selectivity, otherwise impossible, conditions may be such that the failure of the protected line to trip with a fault on it would be far more serious than its tripping on a through fault. In this case positive operation for faults on the protected line would be preferable.

Mr. Rose also has raised a point concerning the interference offered by the communication systems discussed. Since neither the low frequency rectified alternating current pulse system nor the voice frequency telegraph has been applied in the exact manner and for the purpose described, it is impossible to state at this time just how much interference would be offered by these systems. It should be realized that the duration of the interference would be for only a few seconds at very infrequent intervals. Should cases come up where the application of either of these systems appears to be desirable, however, there is little doubt that the interference could be kept within the required limits by the suitable design of the terminal equipment involved.

The methods of protection described are not offered as a panacea for all relay troubles but rather as a useful tool, admittedly costly, which may be the best solution in a great number of situations where the end gained justifies the expense.

Regarding the relative merits of the carrier current and telephone or telegraph circuit systems, the arguments and evidence in favor of either system which have been brought out in the discussions indicate this significant fact—either method is satisfactory and reliable. This is the main thing that we are concerned with here. This paper merely endeavors to indicate the various possibilities in this connection, realizing that the ultimate choice of the system to be used is too largely a matter of local consideration to permit any generalization to be made. With the facilities which are, or can be, made available, this form of protection should go a long way toward solving many of the present difficulties in transmission line relaying.

# Protection of Electrical Apparatus

## Recommended Practise

By Relay Subcommittee,* O. C. Traver, Chairman

**Synopsis.**—*The Relay Subcommittee of the Protective Devices Committee herewith submits its recommendations for the protection of electrical apparatus. These recommendations are based upon a questionnaire and the thirty-seven replies thereto from specialists in this line. The answers were interpreted and codified by a group of twenty experienced engineers particularly interested in the protection of electrical apparatus and circuits. It is hoped that this consensus of the present-day opinion will be the beginning of a series that will be augmented and improved with each periodic analysis and reissue.*

In the past, three papers entitled *Transmission Line Relay Protection* have been presented before the Institute. These indicated the progress of that protective art and discussed in some detail certain methods which were in use at the time they were written.

The last of these, presented in 1930, contained brief notes on the protection of some of the major items of system equipment. It was felt at that time, however, that it would be desirable to have a similar paper presented, devoted entirely to apparatus protection. It is, therefore, the purpose of this paper to present a review of those methods which are in general favor at the present time, and which are considered good practise for the protection of the main items of electrical apparatus.

The information upon which the present paper is based was furnished by representative engineers associated with protective problems in the public utility and industrial fields. In order that the survey might be as comprehensive as possible, 61 copies of a questionnaire were distributed, of which 37 were returned. To guard against answers being given in the light of past practise the transmittal letter laid particular emphasis upon the value of opinions based on future applications rather than upon existing installations. It may therefore be confidently assumed that the condensed results given below express the most advanced ideas of a preponderant body of engineers engaged directly in the study of protective problems.

In a very few cases the average opinion expressed in answers to the questions differs somewhat from the views of the committee. Where such disagreements occur, both opinions are given, together with the reasons which influenced the committee in qualifying the average opinion disclosed by the questionnaire. While agreement was not always unanimous no radically different views were found to exist.

There appears to be a definite recognition of the importance of considering protection problems from two major viewpoints, namely their monetary significance as insurance against damage to equipment, and the less tangible but no less vital relation which they bear to the value of the service in terms of goodwill. The former may readily be computed from existing records of repair costs; the latter is more difficult of evaluation in a pecuniary sense and is consequently susceptible to a variety of conclusions when considered from the angle of return on the capital invested. It is not disputed that this return is large, especially in comparison with the cost of the protective devices, and probably will loom still larger as growth and interconnections continue.

In arriving at its opinions the committee duly weighed the cost of the protective equipment against the value of the results to be expected. This procedure will be found borne out by the kva ratings for which the more expensive methods of protection are recommended. Not only is a large piece of apparatus inherently more costly than a small one but its incapacity to operate due to extensive damage will result in relatively greater inconvenience to the system which it serves.

It should also be remembered that these recommendations apply to the general case and that special situations will arise in which it may be deemed advisable either to raise or lower them. Machines of a certain rating may seem unimportant on a large system and yet attain considerable importance when the system to which they are attached is itself small. In view of the difficulty of basing recommended ratings upon the size of the system the committee felt that it was preferable to consider such ratings upon the more definite basis of intrinsic values and relative costs of protection.

This paper deals particularly with protection against electrical and mechanical failure. When applied to unattended apparatus it overlaps to some extent the field of A.I.E.E. Standards No. 26 on Automatic Stations which also embraces protection against failure of control devices.

### A-C GENERATORS

#### *Whether Steam Turbine, Waterwheel, or Engine-Driven*

*Differential Protection.* In general, differential protection is recommended for a-c generators. This equipment should disconnect the line and field simultaneously and also the neutral if an adequate breaker is provided. In some cases it shuts off the power supply to the prime mover. It should also prevent any dangerous rise of exciter voltage when this machine is directly connected to a hydro-generator or in any other situation in which the exciter may attain excessive speed upon loss of load on the prime mover. As a further precaution against the

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*For personnel of Relay Subcommittee, see end of paper.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

spread of destructive effects following an internal failure, the differential relay may be utilized to liberate carbon dioxide within the shell of any machine which has a degree of enclosure sufficient to render the gas effective.

For generators of either the open or enclosed type at attended stations, differential protection is recommended for ratings of 1,000 kva and above. The average, as derived from the answers to the questionnaire, is 3,000 kva but in view of the intrinsic value and the good results on record the committee felt justified in lowering this figure.

At unattended stations differential protection is recommended for generators rated at 250 kva and above.

From the standpoint of service, a small generator may be frequently as important as a large one, and this is especially true where a small machine is operating directly on a bus with larger generators which are already provided with differential protection. In such a case a fault occurring in the small generator, if not quickly removed, may prove as embarrassing to the service as a similar fault occurring in a large generator; hence differential protection for the small machine is here strongly indicated.

In view of the decreased hazard of insulation failure at low voltages, this form of protection is recommended only on machines rated 2,300 volts and over. This opinion is strengthened by the high current values usually encountered at lower voltages, since these require rather massive terminals and involve greater difficulty in bringing out all the necessary armature leads.

It is recommended that the zone protected by the differential relay include as far as possible all conductors which extend from the generator armature to the bus and the circuit breaker as well.

On generators of 20,000 kva or larger, having two or more parallel windings per phase, and where there is a possibility of turn-to-turn failure, it is recommended that additional protection be provided in the form of a differential relay actuated by a difference of in-phase currents which may occur in the parallel windings. When the neutral is solidly grounded a turn-to-turn fault will usually soon develop into a fault to ground, therefore this protection is recommended particularly in cases where the generator neutral is not solidly grounded. The possibility of circulating currents must also be investigated when parallel balance is contemplated; these however can perhaps be avoided when the machine is designed. Unless this precaution is taken it is possible that circulating currents may cause improper operation of the relay on external faults. With some types of armature windings this relay is also capable of detecting short-circuited turns in the field winding. Since this form of protection is recommended only for large machines its provision adds but a small fraction to the overall cost of the unit.

*Overcurrent Protection.* The use of overcurrent protection for generators in attended stations is not regarded favorably, but at unattended stations it is recommended for back-up protection. When generators at attended or unattended stations are not provided with differential protection, then overcurrent devices, actuated either directly by the armature current or by its thermal effect (replica relay)[1] should be employed. It should be noted however that, because of the rapid decrement of the short-circuit current, care must be exercised in the use of overcurrent relays.

Temperature relays are regarded as a valuable guide to the operator. It is the general opinion that in attended stations they should not disconnect the machine but should only provide a warning signal.

*Field Temperature Protection.* In general field temperature protection is not recommended. An exception however is made in favor of its application to generators which are provided with high-speed excitation and paralleled over long transmission lines. Under short-circuit conditions a heavy field is quickly applied to hold these generators in step. If this field current is not reduced within a reasonable time it is possible that the generator field may overheat without the knowledge of the operator. To guard against this contingency a field temperature relay may be provided to sound an alarm in attended stations and to shut down the unit when the station is unattended.

*Power-Directional Protection with Time Delay.* In the past this combination of protective devices has occasionally been used to prevent motoring on the part of a turbo-driven generator. Since the purpose which it served can now be automatically taken care of at the throttle it is the general opinion that the need for this form of protection no longer exists, except perhaps in rare cases which are not subject to average conditions.

Its use as a protective measure against internal insulation failure is not recommended and can be justified only in the case of old machines which are not provided with sufficient armature terminals for the application of differential protection.

*Bearing Temperature.* Temperature protection is recommended for the main bearings of all unattended machines.

*Protection Against Overspeed.* It is agreed that the usual provision at the prime mover for protection against overspeed is satisfactory for the purpose and that nothing further should be necessary.

*Protection Against Accidental Loss of Field.* Protection against loss of field is recommended for disconnection of the generator at unattended stations. Since a d-c undercurrent relay is the logical device for the purpose it is essential that it be given a suitable time delay to prevent its operation during transients reflected from the armature under short-circuit conditions.

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1. A replica relay operates at a specific temperature of its own mechanism which is designed to have at all times the same temperature as the device protected when subjected to the same ambient conditions.

Other types of temperature relays function on the actual temperature of the machine as determined by elements in direct contact, such as temperature coils or thermocouples.

In attended stations the relay is seldom used, but when used it should not disconnect the generator but may provide an indication to the operator upon the occurrence of this condition.

### FREQUENCY CONVERTERS AND SYNCHRONOUS CONDENSERS

The same recommendations regarding protective equipment for a-c generators apply also to frequency converters and synchronous condensers. In addition, it is felt that some provision (usually time overcurrent relays) should be made for disconnecting a frequency converter under out-of-step conditions. It is also usually advisable to provide time-delayed undervoltage protection for synchronous condensers. No distinction is made between attended and unattended stations in the use of these additional features.

### D-C GENERATORS

At attended stations protection against overcurrent is considered necessary for the protection of d-c generators, and in addition, when these machines operate in parallel with another source of power, provision should be made for protection against reversal of the normal direction of current flow, functioning independently. Additional refinements are usually necessary in unattended stations but the variety and special nature of these devices do not permit of their inclusion in a general condensed report. Some additional information will be found listed in A.I.E.E. Standards No. 26.

*Bearing Temperature.* Temperature protection is recommended for the main bearings of all unattended machines.

*Exciters.* When the exciters are direct-connected and do not operate in parallel it is recommended that no protection against electrical failure be used. For parallel operation on the other hand protection against overcurrent in a reverse direction should be provided. The current setting should be high enough to prevent possible disconnection of the machines when paralleling and during momentary disturbances reflected from the a-c generator armature under a-c short-circuit conditions.

### POWER TRANSFORMERS AND POWER AUTOTRANSFORMERS

*Differential Protection.*

1. Percentage. When circuit breakers are provided for each winding, percentage differential protection is recommended for two or three winding power transformers of 1,000 kva rating and above, either with or without tap changing equipment, whether operated singly or in parallel. As disclosed by the questionnaire the average minimum was found to be 5,000 kva. The committee interprets this to mean that differential protection should always be provided for banks of 5,000 kva and above, if operated in parallel, even though additional breakers must be purchased.

When the bank is part of a line and provided with a circuit breaker on the bus side only, certain modifications of the foregoing method are recommended. These will be found under a subsequent heading.

When the necessary circuit breakers are provided for complete isolation of a power autotransformer, percentage differential protection is recommended for an equivalent physical capacity of 1,000 kva and above. It is also recommended that all banks of power autotransformers operated in parallel and having an equivalent physical capacity of 5,000 kva and above be provided with differential protection, even though additional breakers must be purchased. The autotransformer output rating corresponding to 1,000 or 5,000 kva of equivalent physical capacity will of course vary with the ratio of voltage transformation.[2]

It is recommended that the circuits embraced by the differential protection include all conductors up to and including the circuit breakers on each side of the transformer.

2. Overcurrent (Differentially-Connected). When differentially-connected overcurrent relays are used in place of percentage differential protection for any of the foregoing types of transformers, it is recommended that they be of the inverse-time type. The time characteristic prevents operation on external faults since these may otherwise create sufficient unbalance at the relay to bring about needless tripping.

*Back-Up Protection.* In addition to differential protection, overcurrent or other back-up protection (not necessarily at the transformer itself) should be provided at some point on the source side to protect the transformer against the effects of sustained excess currents which may arise from the failure of protective apparatus to clear faulty equipment. Temperature relays, either operated by embedded coils or of the replica[1] type, are also occasionally employed.

When a transformer is not protected by differential methods it is always recommended that overcurrent protection be provided.

*Smoke or Gas Detectors.* Insufficient experience in the United States with these devices precludes the expression of an opinion regarding their value, or their possibilities, as a means of transformer protection.

*Transformers Having Breakers in Low Side Only.* Power transformers which have a circuit breaker on the bus side only, the other side being connected directly to the line, are generally treated as part of the line and consequently included in the line protection. When the latter is protected by distance or directional overcurrent relays it is suggested that differential protection also be considered for the power transformer and arranged to trip the transformer breaker. Under some

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[2] In general the ratio of the equivalent physical capacity of an autotransformer to its kva output is equal to the percent voltage transformation, based on the high voltage thus:

$$\frac{\text{Equivalent capacity}}{\text{Rated output}} = \frac{E_1 - E_2}{E_1} = 1 - \frac{E_2}{E_1}$$

where $E_1$ is the high and $E_2$ the low voltage.

circumstances this will result in speedier isolation of the disturbance. For example, if a fault occurs in the transformer during a period when normal power is flowing from the bus towards the far end of the line, the directional relay at the distant end cannot respond to the fault current until it has grown to proportions sufficient to overcome the torque produced by the normal direction of power. By quickly tripping the bus breaker however the differential relay interrupts the normal flow of power and thus frees the distant directional relay of its normal power torque. It then responds to the lower fault current and the transformer is isolated before serious damage can result.

*Magnetizing Transients.* The replies to the questionnaire disclose that trouble from magnetizing transients is of sufficiently frequent occurrence to warrant some discussion regarding means for overcoming its effect on the protective relays. Inrush magnetizing currents being absorbed within the transformer disturb the balance at the differential relay, and may cause undesirable tripping of the circuit breakers. The ability of sources of large capacity to maintain full voltage on the transformer terminals at the inception of the transient adds greatly to the magnitude which it may attain. These abnormal currents are primarily brought about by the residual flux. Should this be of appreciable magnitude, and in a direction such that the flux change required by the voltage at the moment of closure will push the total flux above the knee of the saturation curve, it follows that the magnetizing current will be unduly large. The difficulty is more pronounced on 25-cycle systems.

Special or additional equipment is available for preventing tripping during the magnetizing transient and this precaution is always necessary when high-speed relays are used. The more common types of relays, however, being slower will usually ride safely through the transient, and where such relays are employed, the committee feels that the addition of the special equipment referred to should be based more properly upon the trouble which the user encounters.

It is also pointed out that undesired operation of differential relays may possibly arise at the moment of clearing an external fault occurring in the vicinity of the transformer. Just before the fault is cleared the voltage at the transformer may have fallen to zero and immediately afterwards will tend to return to normal, thus possibly simulating the conditions obtaining at initial magnetization. Experience of trouble arising from this cause having been meager, the committee does not feel called upon to suggest measures for its avoidance.

## A-C MOTORS

*Differential Protection.* An analysis of the replies to the questionnaire indicates a general agreement on the desirability of differential protection for large a-c motors, the average minimum rating at which it should be applied being 1,750 hp. It was the opinion of the committee that motors of 2,000 hp and above, with a minimum rating of 2,200 volts, should be provided with differential protection.

*Overcurrent Protection.* In addition to differential protection, temperature relays, either of the replica type, or operated by embedded coils, are recommended for protection against excessive or prolonged overloads. Due to loss of cooling by windage the latter may more accurately represent the true temperature of the motor under stalled-rotor conditions.

Below the 2,000 hp rating given above for differential protection it is recommended that motors be provided with inverse-time overcurrent and instantaneous overcurrent protection, the instantaneous relay being set above the stalled-rotor current to take care of severe short circuits without delay.

*Undervoltage Protection.* When undervoltage protection is used it should have sufficient *time delay* to enable the motor to coast through temporary dips in voltage. Undervoltage protection is seldom used for motors which start on full voltage since these will automatically come up to speed when normal voltage is resumed.

*Phase-Rotation Protection.* Phase-rotation relays to guard against reversal of phase-rotation are recommended chiefly for use at unattended stations and in elevator service.

*Protection against Unbalanced Phase Currents.* Dielectric failure results in unbalanced phase currents. This condition may be detected by a relay which is actuated either by the unbalance phase currents themselves or by their corresponding negative phase-sequence components. When differential protection is not possible or practicable these relays are frequently used at unattended stations, but it should be remembered that phase-balancing action will produce unbalanced conditions in sound motors and thus may lead to erroneous tripping on the occasion of an external unbalanced fault.

*Bearing Temperature.* Temperature protection is recommended for the main bearings of all unattended machines.

*Power Station Essential Auxiliary Motors.* It is important that motors driving essential power station auxiliaries be not removed from service except as a last resort, and then in the interest of service, their isolation should be accomplished as promptly as possible. For this reason it is recommended that such motors be protected by instantaneous overcurrent relays set well above the stalled-rotor current. When temperature relays are used in connection with these motors they should be arranged to sound an alarm only. Phase-balance relays or negative phase-sequence relays are not recommended for essential motors because of the phase-balancing tendency of polyphase motors already mentioned under the preceding heading.

It is not common practise to ground the neutral of the supply source for essential motors but if for any reason such a condition exists, then ground relays may be advantageously added to the protection.

### D-C MOTORS

Fuses are considered sufficient protection for small d-c motors. For medium and large sizes, overcurrent and undervoltage protection, usually self-contained in the air circuit breaker itself, are recommended. Where the machine is very large, and its service correspondingly important, additional refinement in the form of temperature protection is desirable.

*Bearing Temperature.* Temperature protection is recommended for the main bearings of all unattended machines.

### SYNCHRONOUS CONVERTERS

Synchronous converters require protection on both the a-c and the d-c sides. On the a-c side inverse-time overcurrent protection is recommended to trip the oil circuit breaker. In addition, when the d-c side is grounded and flashover possible, an instantaneous flashover relay, connected between the machine frame and ground, is recommended to disconnect both the a-c and d-c sides. If the possibility of flashover exists, and no flashover relay is provided, it is recommended that the overcurrent protection on the a-c side be instantaneous instead of inverse-time.

For the d-c side instantaneous overcurrent protection is recommended, and in addition, when the machines are operated in parallel, separate reverse current protection should be provided to disconnect the converter when power flows toward it from the d-c bus. Most synchronous converters are equipped with mechanical overspeed devices: these should trip the d-c circuit breaker and, if the system is subject to runaway speeds, the a-c circuit breaker also.

Additional information will be found listed in the A.I.E.E. Standards No. 26 on Automatic Stations.

*Bearing Temperature.* Temperature protection is recommended for the main bearings of all unattended machines.

### RECTIFIERS

Rectifiers are almost universally automatic in their operation and it is considered that recommendations for their protection are adequately covered by the tabulation given in the A.I.E.E. Standards No. 26 on Automatic Stations.

### BUS PROTECTION

*Differential.* All failures occurring on important buses should be promptly isolated. Differential methods which balance all currents entering and leaving the bus are recommended for this purpose. In such applications it is important that the ratio characteristics of the current transformers in the differential circuit should hold substantially within the relay setting at the maximum primary currents so that incorrect operation cannot occur on external faults. With a given core design, the higher the transformation the more accurate is the ratio curve. The desired conditions can best be achieved by the use of a single ratio for all current transformers taking part in the differential scheme. If it is not possible to follow this recommendation and current transformers of different ratios are employed, then auxiliary current transformers must be used in the secondary circuits to equalize the different ratios at the balance point.

It should be noted, however, that when an auxiliary transformer is used to increase the ratio of a low-ratio line current transformer a double handicap is placed upon the equipment compared to that which would result from the use of a single current transformer having the same total ratio. This follows because:

a. In the lower ratio transformer ratio error begins at lower currents.

b. The additional burden imposed by the auxiliary transformer also has the effect of increasing the ratio error in the line current transformer.

Under certain conditions of power flow, restraint may be advantageously used in the differential relay. In general however these conditions do not obtain, and hence the effect of restraint, if used, cannot be predicted with any degree of certainty.

*Ground Fault Bus.* When the system is grounded, a ground fault bus may be used, each protective relay being operated by a current transformer inserted in the common ground connection for its particular bus section. If provision be made for the application of this method during the station design period, its installation does not involve the serious constructional difficulties that may be encountered in attempting to introduce it in an existing station.

### NEUTRAL GROUNDING EQUIPMENT

*Grounding Resistors and Reactors.* It is recommended that grounding resistors and reactors be protected by overcurrent or temperature relays which, after a short delay sufficient to allow line protection to function, will initiate an alarm to indicate that a ground fault has not been properly cleared. This procedure is designed to give the operator an opportunity to carry out a course of action already decided upon to govern such conditions.

Fortunately the trend toward the use of resistors having a two-minute ground fault capacity allows reasonable time for disconnecting manually the source of the trouble without opening or short-circuiting the resistor. Should either of these latter courses become necessary however it would seem preferable from the protective standpoint to maintain the system ground by short-circuiting the resistor, unless this action nullifies the purpose, such as the prevention of telephone interference, for which the resistor was originally installed.

*Grounding Transformers.* Protection for grounding transformers of either the zig-zag or Y-delta type should follow substantially along the lines indicated for grounding resistors and reactors in so far as the effects of sustained external ground faults are concerned.

For protection against internal faults, two forms of differential protection may be used. In one of these, three differentially-connected overcurrent relays are operated in Y from the delta-connected secondaries of three current transformers located in the line side of the grounding transformers. This is equivalent to differential protection on an ordinary transformer with no load being carried by the secondary, since in the grounding transformer the secondary delta winding carries no external load. It provides protection against both turn-to-turn short-circuit and internal grounds occurring in the transformer, or on the conductors between it and the current transformers.

The other and generally less desirable method compares the zero phase-sequence currents on both sides of the grounding transformer by means of three line current transformers connected in parallel and balanced against a current transformer connected in the neutral. Since turn-to-turn faults do not result in zero phase-sequence currents, this method does not protect against such faults, but functions on faults to ground only.

In applying these forms of protection it is important that the characteristics of the operating current transformers be checked up to maximum short-circuit values.

## IMPRESSIONS

In looking over the preceding recommendations one cannot fail to be impressed by the prominent place still occupied by the simple overcurrent relay in the protection of a wide range of electrical apparatus. Even where it has been supplanted in the first line of defense by more highly selective devices, it is still relied upon as a safeguard of last resort. Nor is this surprising when it is remembered that in any analysis of the destructive effect of dielectric rupture, the major damage is brought about by the thermal, or magnetic effects of high currents. This thought tends to strengthen the belief that the persistence of the overcurrent relay as an important protective agent is destined to extend for a considerable period into the future.

Growing interconnections have brought increasing problems to the operating engineer and his demand for the rapid isolation of faults has brought similar problems to the relay designer. In recent years the trend has been toward the attainment of greater speeds with increased selectivity. Nor is progress in the relay field alone to be recorded; current transformers offering uniform characteristics up to exceptionally high current values are procurable, and circuit breakers capable of interrupting these currents in a brief period of time have been developed.

No discussion on protective methods can be complete without some reference to the primary position taken by the insulation itself. That improvements have been effected in apparatus insulation during recent years cannot be questioned, but there are quite obvious economic factors limiting extension of the insulation to a point of absolute dependability under any and all conditions. Direct lightning is still a thing to be feared and its dangers cannot economically be overcome entirely by increased insulation. Beyond the point at which greater insulation becomes impracticable, the relay must always find its place in the protective economy of the electrical system.

In conclusion the committee desires to extend its thanks to all those who gave so generously of their time in responding to the questionnaire, and without whose collaboration the work of the committee in conducting this survey would have been doubly arduous and its results of considerably less value.

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| P. H. Robinson, | Houston Lighting & Pr., | Houston, Texas. |
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| E. B. Wagner, | Lehigh Valley Coal Co., | Wilkesbarre, Pa. |

## Discussion

**Philip Sporn:** The Relay Committee has taken in this report a step that has distinct possibilities for a great deal of good in the protection field. The placing before the Institute membership and the entire engineering profession of a complete set of suggested relay practise covering the field of electrical apparatus, together with a discussion of the underlying principles, is bound to stimulate discussion and clarify the basic ideas of relay protection. But, in commending the step it is well to point out the grave danger connected with such a procedure: there is the danger that this may result, or may tend to result, in a codifying of existing practice. In line with this, it may be well for the Relay Subcommittee to re-title its recommendations and call them "Suggested Practice" instead of "Recommended Practice." The distinction between the two may be very fine, but is rather important. It is very important, too, that the Committee avoid setting itself up as an arbiter of what is sound practise, that it avoid in so far as possible a pontifical attitude in a matter that is as flowing and vigorously alive as the relay art. There is no question, for example, that today's relay practise is a tremendous advance over the practise commonly employed a decade ago, but by the same token it must be kept in mind that the relay art of a decade hence will represent in all probability a similar advance over the present art and present practise. All this means, therefore, frequent and careful revision of this report.

Again, it cannot be too strongly emphasized, and the Relay Committee is the logical group to do it, that relay protection is a form of insurance: Insurance of apparatus and insurance of service, and that as insurance, it has to compete against other forms of insurance: and that the premiums represented by the cost of the insurance have to be carefully weighed against the benefits derived. This is but another way of saying that relay protection is in one of its important aspects an economic problem, and only when it is considered as such, are we likely to arrive at the sound engineering basis for good practice.

I cannot help but comment on the Relay Committee's well merited praise of the overcurrent relay. Only, I do not believe that the committee has been strong enough in its statement. It is a fact that the value of the overcurrent relay is recognized today probably to a greater extent than ever before in its history and that it probably occupies today a position in the front line of defense of electrical apparatus and equipment that it has never occupied before. For utmost simplicity and reliability, there is no relay device that gives as much protection for a given expenditure as an overcurrent relay. This in spite of the fact that it almost never can give 100 per cent protection. Properly applied, however, it is a most excellent guardian for the protection of equipment and service.

**O. C. Traver:** The relay subcommittee appreciates the pertinent comments of Mr. Philip Sporn and others who have given attention to this paper.

In presenting its report the committee sought to reflect the best generally accepted practice in relay protection, and certainly did not wish to create an instrument that would impose liability on the part of any operating company that might prefer to follow relay practices other than those described. Therefore the report is, in effect, an outline of "Suggested Practices" and the word "Recommended" in the title must not be taken as imposing a mandate.

Clarification and amplification of another point also seem desirable in the light of the discussion and as a result of further consideration. The paragraph entitled "Undervoltage Protection" has, by subsequent committee action, been entirely superseded by the following:

*Undervoltage Protection.* When undervoltage protection is used it should have sufficient *time delay* to enable the motor to coast through temporary dips in voltage. An exception is made in very rare cases which definitely require immediate action. Induction motors which normally start on full voltage will resume speed without injury to themselves when normal voltage is restored. In such cases undervoltage protection is not required for the motor itself but is frequently necessary to safeguard the operator or the product against unexpected restarting after the motor has once stopped.

# Application of Phase Sequence Principles

## To Relaying of Low-Voltage Secondary Networks

BY H. R. SEARING[1] and R. E. POWERS[2]
Fellow, A.I.E.E Associate, A.I.E.E.

It is the purpose of this paper to present an improved network relaying system utilizing a conventional single-phase relaying element and contactor type overcurrent elements excited by symmetrical phase sequence components to represent completely power flow conditions and control protector operation on a three-phase four-wire secondary network system.

The low-voltage alternating-current network was conceived and developed in order to meet the need for an alternating-current system of distribution that would provide high quality service and compete with the direct-current system in reliability and economy. In its present form, it consists of a distribution network, served by a plurality of feeders, with intermediate voltage transformation and network protectors. The use of the present arrangement dates from the development of the network protector which fulfilled several functions and may be described as a means to connect and disconnect each of the feeders to the network under proper conditions.

The protector consists of a circuit breaker and necessary operating relays located in each of the feeds to the network. Each main feeder provides a multiplicity of feeds to the network through low-capacity transformers, (50 to 1,000 kva) and it is the function of the protector to connect to or disconnect from the feed to the network under proper conditions.

The development of the low-voltage network in metropolitan areas has been very rapid and new problems have continually arisen. The major change in certain localities has been in the supply to the network and has developed from a multiple supply from a single source to multiple supplies from several sources. With the increase in network loading new supplies to the network have been at higher voltage, and voltages of 4, 13, 22, and 27 kv are regularly used. Vertical type building networks of the concentrated or "spot" type are not uncommon.

The principal problem that has arisen from the developments outlined above is that of preventing the excessive number of protector operations that result from power interchanges between feeders through the network. Power reversals, at specific points in any general network under normal operating conditions, are not uncommon and are attributed to:

1. Periodic heavy shunt load drawn from substation buses from which network feeders emanate.
2. Individual feeder loading and induction regulator action.
3. Phase angle and voltage differences in individual generating sources due to loading, etc.
4. Starting of large induction-synchronous motor.
5. Elevator regeneration during braking periods.

Experience has shown that in *certain localities* network protectors when adjusted to trip on reverse magnetizing watts operate at the *rate* of from 10 to 15 thousand times per year per switch as a maximum and that the average number of switch openings are at the rate of from 3 to 5 thousand operations. The number of operations does not indicate incorrect relay performance as the standard unit is designed to operate on small power reversals. This condition causes undue wear on the protector and disconnects a supply source from the network that should be available at all times.

In the practical operation of network systems this duty is reduced by adjusting the relay to trip at increased values of reverse energy; that is, the protector is adjusted so as not to open on the reverse magnetizing watts of a single supply transformer but at some higher value depending upon local conditions. The methods employed to extend the tripping range of a standard network relay (20-30 per cent) ordinarily require additional equipment having moving parts. As the number of protectors with increased reverse power settings becomes large, difficulty is encountered in tripping protectors when the supply breaker is opened. Load-back methods must be resorted to or men sent to the vault or manhole to disconnect protectors.

In an endeavor to produce a network relaying system that would meet the requirements of the original relay specifications and in addition be sufficiently broad in its characteristics to permit the flow of reverse energy encountered in normal operation, phase sequence currents and voltages have been utilized in a new network relaying system. These single-phase symmetrical components of current and voltage replace the three line-to-neutral voltages and phase currents ordinarily used and completely indicate power flow conditions. The preliminary mathematical analysis, subsequent relay design and field tests have proved the correctness of the theory and application, and indicates the practicability of utilizing sequence components in relaying systems producing a simplification of apparatus with improved characteristics.

Symmetrical component quantities may be considered as the mathematician's conception of a polyphase system, however, the quantities concerned are real, not imaginary, and are amenable to actual measurement. Through the work of Fortescue, Evans, Wagner and others, phase sequence segregating filters have been developed permitting the isolation of any or all of the phase sequence currents and voltages, which may be applied to conventional elements to secure metering or relaying functions in response to changes in sequence quantities.

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[1] New York Edison Co., and United Electric Light & Power Co.

[2] Westinghouse Electric & Mfg. Co.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

A review of network relay requirements, embracing application to systems employing low- and high-voltage feeders from segregated substations and generating sources, feeding into a general network supplemented by spot networks, indicate the necessity for:

1. A master directional element to indicate direction of power flow.
2. Phasing features to control protector closing.
3. Selective tripping features in the relaying system to prevent opening of the protector upon reversal of energy through the switch during normal system operation with the feeder breaker connected to the source.
4. Sensitive tripping when the feeder is disconnected by the opening of the generating or substation breaker.

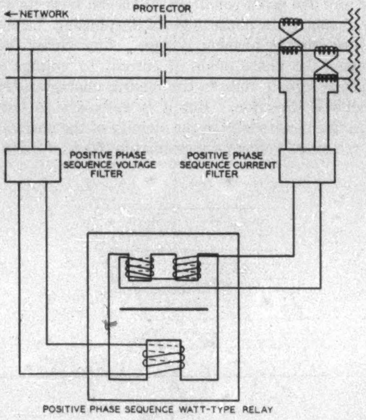
←NETWORK
PROTECTOR
POSITIVE PHASE SEQUENCE VOLTAGE FILTER
POSITIVE PHASE SEQUENCE CURRENT FILTER
POSITIVE PHASE SEQUENCE WATT-TYPE RELAY

Fig. 1

These requirements are fulfilled by the new relay system.

The master directional element consists of a single-phase watt relay operating on positive phase sequence voltage and current. This element is responsive to the direction of flow of positive phase sequence power under all conditions (Fig. 1).

To be generally satisfactory from the standpoint of performing the phasing features the relay must

1. Check phase sequence.
2. Check any interchange of phase wires on the supply feeder.
3. Connect the protector to the grid only when power will be fed from the feeder into the network.
4. Prevent any "pumping" of protectors, when the supply breaker is open and a defective unit remains in the closed position, thus energizing the feeder from the network.
5. Permit closing on a dead network.

Phasing is accomplished in the new relay by the use of voltage segregating filters and auxiliary windings on the watt relay used as a master directional element.

A voltage segregating filter of the positive phase sequence type when connected to a system of phase sequence *abc* delivers at its output terminals a voltage proportional, under all conditions, to the positive phase sequence voltage. If the supply voltage is balanced, the output of the network will be proportional to and bear a definite phase relationship to the line to neutral voltage. If for any reason, two phases are interchanged the supply system phase sequence, (order of appearance of maxima) is changed from *abc* to *acb* and when impressed on a sequence segregating voltage filter designed to deliver positive phase sequence voltage with normal phase sequence *abc* the output of the network will be zero, if the supply is balanced. During phasing periods experience and test have shown that balanced voltage conditions exist on incoming feeder circuits although phase sequence may be incorrect. Certain progressive interchange of leads on the supply circuit gives rise to proper phase sequence *abc* but rotated 120 deg or 240 deg in the counter-clockwise direction with respect to normal network voltage. Under this condition the output of the network is normal but rotated 120 deg or 240 deg respectively.

The fundamental characteristics of voltage sequence segregating filters in response to changes in phase sequence, polarity reversals, and phase advancement discloses the possibility of using phase sequence quantities to accomplish phasing functions. Obviously, single-phase representation of the selected quantity may be employed thus permitting the use of a single-phase relay to adequately represent a polyphase system.

Drawing on the experience gained with the present protector relaying scheme, it has been demonstrated that the phasing characteristics can be secured by adding to the upper or current poles of the watt type relay phasing windings excited by voltage across the open switch. The potential or lower pole of the relay is excited by voltage from the secondary network. The network voltage is chosen as reference point as it is necessary to check the incoming feeder in magnitude, phase position and sequence against that of the network to insure proper operation.

Following the conventional design of relay element "watt" and "phasing" characteristics can be secured on a single-element relay (see Fig. 2) by the use of

1. Positive phase sequence voltage and current for watt indication.

2. Network positive phase sequence voltage and the difference between network positive phase sequence voltage and incoming feeder positive phase sequence voltage (difference positive phase sequence voltage across the open protector) to perform phasing functions.

The combined phasing characteristic of the present *CN*-3 master relay and the *CNA* phasing relay is shown in Fig. 3, indicating that protector closure can occur only in a rather limited range due to the combined phasing features of both relays.

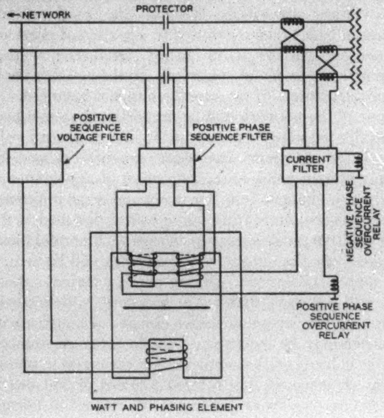
NETWORK
PROTECTOR
POSITIVE SEQUENCE VOLTAGE FILTER
POSITIVE PHASE SEQUENCE FILTER
CURRENT FILTER
NEGATIVE PHASE SEQUENCE OVERCURRENT RELAY
POSITIVE PHASE SEQUENCE OVERCURRENT RELAY
WATT AND PHASING ELEMENT

Fig. 2

In utilizing phase sequence quantities to develop a relay with settings, 10-100 per cent of transformer rating, it is not necessary to confine the "closing region" to the limited range employed in the present standard equipment but may be extended to embrace *leading* voltages lower in magnitude than the network voltage. In actual practise these voltages occur very infrequently as incoming feeder voltage is high and leading, not low and leading.

To prevent "pumping" of protectors on systems employing high-voltage underground feeders the phasing characteristics must be such that the relay contacts will not close when the incoming voltage is high and lagging indicating a "closed" protector exciting the capacitance of the cable from the network, with consequent voltage rise across the secondary mesh and network transformer. Mathematical analysis, field tests and a check on the performance of existing relays indicate that to avoid pumping conditions the closing characteristic of the network relay as a phasing device, must be rotated through approximately 60 to 70 deg from the horizontal, as shown in Fig. 4. While linear closing characteristic of this nature would be excellent for a non-sensitive type relay, a study of Fig. 4 will show that the linear characteristic intersects the voltage $Ec_1$ and would permit protector closure due to cyclic rotation of conductors that produced normal phase sequence *abc* but advanced counter-clockwise 120 deg with respect to the reference or secondary network voltage.

The phasing voltages encountered in normal system operation are relatively small, having a magnitude of only a few volts. Under the conditions outlined above, the phasing voltage would approximate in magnitude the line-to-line voltages $E_p$, Fig. 4, which is many times the normal phasing voltage. It is desirable to have the phasing characteristic linear in the range of normal phasing voltages, but to deviate therefrom at higher values so as to avoid possible improper operation, under certain system conditions that are a function of system repair and extension involving the human element.

It is recognized that the slope of the closing characteristic may be changed by governing the relationships between the flux on the upper and lower pole of the relay, for any one given condition. This can be accomplished by changing the phase angle of the phasing current with respect to the phasing voltage. Any factor that decreases the phase angle of current to voltage in the phasing circuit rotates the closing characteristic in a clockwise direction. But it is necessary to have the closing characteristic in the vicinity of the normal value of reference voltage approximately 60 to 70 deg from the horizontal to prevent pumping, therefore, the normal angle of current to voltage is set by that requirement. However, the range of phasing voltages is very large and devices can be added to the phasing circuit of the saturating type or of the form that produces resistance changes with current flow such as the conventional phasing lamp. With normal phasing voltages saturation effects and resistance changes do not occur and the phasing characteristic is linear. With increasing phasing voltages these changes occur and the ratio of

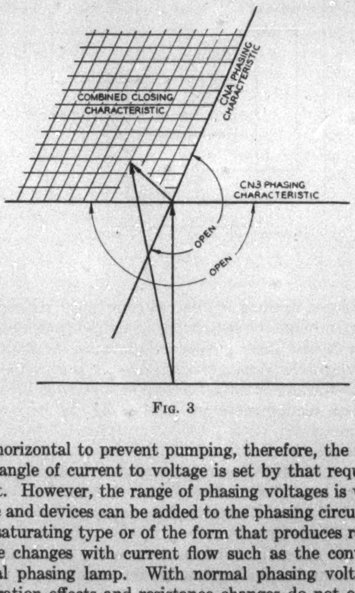
COMBINED CLOSING CHARACTERISTIC
CNA PHASING CHARACTERISTIC
CN3 PHASING CHARACTERISTIC
OPEN
OPEN

Fig. 3

reactance to resistance varies, resulting in change in the angle between phasing coil currents and voltage, causing a deviation from a straight line in the phasing characteristic as shown dotted in Fig. 4. The changing characteristics of the phasing circuit, with increased phasing voltages must be such that the characteristic curve does not intersect a voltage vector of normal magnitude rotated 120 deg counter-clockwise to prevent false closure in event of accidental cyclic rotation of conductors during cable splicing producing a 120 deg shift of positive phase sequence voltage. The changing characteristics on the upper part of the phasing curve encroaches upon the possible range of back feed voltages existing due to a single "closed" protector on systems supplied by underground high voltage cables. Analytical work and field tests indicate that the proposed curve is sufficiently broad in its characteristics to perform satisfactorily on existing and proposed systems employing 13- and 27-kv feeder circuits.

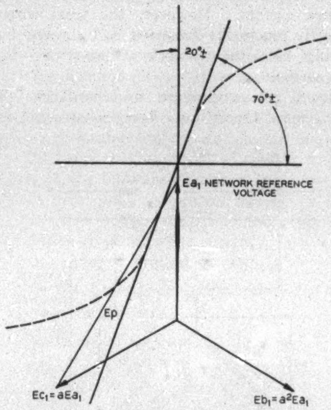

FIG. 4

Selective and sensitive tripping is obtained by the combined operation of the master directional element and current magnitude relays. Selective tripping refers to relay operation with balanced reverse power flow and would be above the range produced by the inherent system conditions during normal operations. This feature reproduces the results obtained from present network relays when increased reverse power settings are used.

The current magnitude relay used for selective tripping is a simple single-phase contractor type relay energized by positive phase sequence current. When positive phase sequence current of sufficient magnitude has closed the contacts of this relay, the potential coil of the master directional relay is energized and tripping of the protector occurs if the power flow is from the network to the feeder.

Sensitive tripping refers to relay operation at times when the supply breaker is open. A current magnitude relay energized by the negative phase sequence component of the line current and operating in a manner similar to the relay used for selective tripping, provides for sensitive tripping.

A current segregating filter provides the symmetrical components of line current.

Negative phase sequence current does not exist in a perfectly balanced polyphase system. In the practical low-voltage network system under normal operation negative phase sequence current exists only in very minor quantities. However, every unbalanced load or fault acts as a source of negative phase sequence voltage and current transforming or converting from positive phase to negative phase sequence order. The same considerations apply to zero sequence quantities if the system or mesh is grounded. We thus have a quantity which is absent normally but is available under abnormal conditions to provide a discriminating means whereby tripping functions may be initiated.

Therefore, if the selective tripping combination is supplemented by a negative phase sequence overcurrent relay, tripping of the protector can be limited to fault or reverse unbalance conditions on the high-tension feeder.

The appearance of negative phase sequence current, at a time when positive phase sequence power is from the grid to the feeder indicates abnormal conditions such as a primary fault or primary load unbalance and warrants protector opening. The negative phase sequence current element can be set at low values since only small quantities of negative phase sequence current are normally present in the system.

Since the sensitive tripping arrangement provides for clearing the protector in case of faults, it would appear that the selective tripping feature is unnecessary except for the condition of a three-phase balanced feeder fault or to avoid damage to individual protectors from overloading during abnormal system conditions not identified with any particular feeder. Field experience may show that the selective tripping arrangement can be eliminated.

While tripping functions are, therefore, provided for all types of primary faults and eliminated for all secondary faults, provision must be made for clearing of the protectors for inspection or construction purposes.

This is accomplished by providing a source of negative phase sequence current. A small induction-synchronous motor-generator set arranged as in Fig. 5 and connected to the feeder at the generating source after opening the feeder breaker may be used. The voltage required will be relatively low as only small values of negative phase sequence current are required and the impedance to the flow of negative phase sequence current is the short circuit impedance of the negative phase sequence mesh. Thus the kva capacity of equipment required and the current flow during operation will be so low that voltage disturbance will not result on the secondary network.

In stations equipped with ground and test bus, the motor-generator set can be connected to it through suitable transformers and without starting apparatus.

The majority of transformers used in network distribution are delta connected on the primary winding, and the neutral of the feeder circuit usually is established at the generating station. Upon opening of the feeder breaker the feeder circuit is ungrounded and negative phase sequence current can be produced by earthing one conductor of the delta-connected circuit which effectively short-circuits out the capacitance of that conductor and increases the voltage on the capacitance to ground of the other conductors. This is equivalent to loading of two phases only, thus creating a load unbalance and giving rise to negative sequence current. The magnitude of current will depend upon capacitance and thus upon the type, length and voltage of the circuit involved. Higher-voltage underground cable circuits, 13 kv and above, will be most effective in producing negative sequence current when one conductor is earthed.

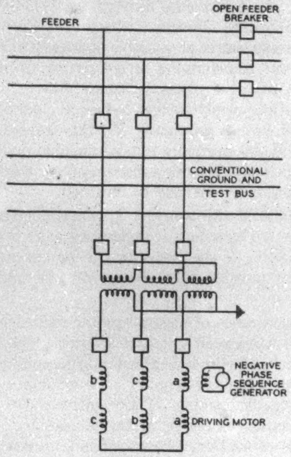
FEEDER
OPEN FEEDER BREAKER
CONVENTIONAL GROUND AND TEST BUS
b
c
a
c
b
a
NEGATIVE PHASE SEQUENCE GENERATOR
DRIVING MOTOR

Fig. 5

Any type of apparatus that places an unbalanced load between phases produces negative sequence current and any simple loading device can be employed. Phase-to-phase loading is preferable to phase-to-ground loading.

Apparatus for the generation of negative phase sequence current may be located in the high-tension circuit at the generating station or in the low-voltage network on the transformer side of a single protector per feeder.

As pointed out previously, negative phase sequence current of appreciable magnitude is normally not present in the system, but does appear under fault conditions or unbalance. Therefore, negative phase sequence current offers a ready means to discriminate between normal and abnormal circuit conditions.

It is interesting to note that phase angle or balanced difference voltage between various points in the network produce circulating currents of positive sequence order. In the practical system, operating experience and field test indicate that the so-called circulatory currents are predominately positive phase sequence and contain only negligible components of negative phase sequence currents. This current is produced by phase angle and voltage difference in the three phases of the system due to slight unbalance in phase loading. Individual load unbalance, single-phase line-to-line or line-to-neutral load in the secondary network produces negative phase sequence current. However, the total three-phase loading is practically balanced as indicated by commercially balanced network voltages and balanced feeder currents.

Network relays designed in accordance with the above general theory have been constructed and are now in operation on the system of the United Electric Light and Power Company in New York where approximately 400 relay months of service has been secured. The satisfactory performance of the relays in the most severe type of service that could be selected within the system, indicate the adequacy of the fundamental principles and subsequent relay design. The general features of relay design and operating experience will be outlined in a companion paper by Messrs. M. A. Bostwick and H. S. Orcutt.

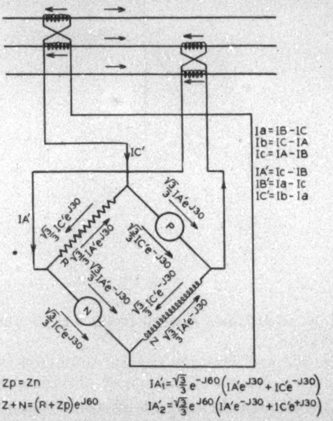
IC'
IA'
Ia = IB - IC
Ib = IC - IA
Ic = IA - IB
IA' = Ic - IB
IB' = Ia - Ic
IC' = Ib - Ia
P
N
R
Z
$\frac{\sqrt{3}}{3} IA'e^{J30}$
$\frac{\sqrt{3}}{3} IC'e^{J30}$
$\frac{\sqrt{3}}{3} IA'e^{J30}$
$\frac{\sqrt{3}}{3} IC'e^{-J30}$
$\frac{\sqrt{3}}{3} IA'e^{-J30}$
$\frac{\sqrt{3}}{3} IC'e^{-J30}$
$\frac{\sqrt{3}}{3} IC'e^{J30}$
$\frac{\sqrt{3}}{3} IA'e^{-J30}$
Zp = Zn
Z + N = (R + Zp)$e^{J60}$
$IA'_1 = \frac{\sqrt{3}}{3} e^{-J60} (IA'e^{J30} + IC'e^{-J30})$
$IA'_2 = \frac{\sqrt{3}}{3} e^{J60} (IA'e^{-J30} + IC'e^{+J30})$

Fig. 6—Combination Current Filter to Indicate Positive and Negative Phase Sequence Current

It is our desire to express appreciation for the assistance given by Dr. C. L. Fortescue, C. F. Wagner, R. D. Evans, G. R. Milne and W. A. Lewis in analyzing and applying phase sequence principles to the relaying system used in low-voltage networks.

## Appendix 1

### COMBINATION SEQUENCE SEGREGATING FILTER DESIGNED TO DELIVER SIMULTANEOUSLY POSITIVE AND NEGATIVE SEQUENCE CURRENT

The determination of a given phase sequence current requires that the remaining two current components be eliminated, that is not passed through the meter element. In three-phase ungrounded operation, zero phase sequence currents are not present and are automatically eliminated. In grounded neutral systems zero phase sequence current is present and means must be provided to eliminate the possibility of its appearance in the relay element.

*Elimination of Zero Sequence Currents.* Fundamentally, zero sequence currents in the three line conductors are equal and in phase. If cross-connected current transformers are used, as shown in Fig. 6, for the supply to a sequence segregating filter the output of the two current transformers will not contain zero sequence currents. Inasmuch as the output of the two current transformers is the difference between the two-phase currents the zero phase sequence current is automatically cancelled and the output contains only positive and negative phase sequence current.

In Fig. 6, following recognized convention

$$IA' = Ic - Ib = aIa_1 + a^2Ia_2 + Ia_0 - a^2Ia_1 - aIa_2 - Ia_0$$

$$= (a - a^2)(Ia_1 - Ia_2) = J\sqrt{3}\,(Ia_1 - Ia_2) \qquad (1)$$

$$IC' = Ib - Ia = a^2Ia_1 + aIa_2 + Ia_0 - Ia_1 - Ia_2 - Ia_0$$

$$= (a^2 - 1)\,Ia_1 + (a - 1)\,Ia_2$$

$$= \sqrt{3}\,e^{j210}\,Ia_1 + \sqrt{3}\,e^{j150}\,Ia_2$$

$$= J\sqrt{3}\,(aIa - a^2Ia_2) \qquad (2)$$

From equations (**1**) and (**2**) it is seen that the positive and negative phase sequence currents in $IA'$ and $IC'$ are directly proportional to the corresponding components of $Ia$ and $Ic$

$$IA_1' = J\sqrt{3}\,Ia_1 \qquad (3)$$

$$IA_2' = -J\sqrt{3}\,Ia_2 \qquad (4)$$

With elimination of the zero phase sequence component of current by the use of cross connected current transformer

$$IA_o' = 1/3\,(IA' + IB + IC') = 0 \qquad (5)$$

$$IB' = -(IA' + IC') \qquad (6)$$

by definition

$$IA_1' = 1/3\,(IA' + aIB' + a^2IC') \qquad (7)$$

Substituting (**6**) in (**7**)

$$IA'_1 = 1/3\,(IA' - IA' - IC' + a^2IC')$$

$$= 1/3\,(1 - a)\,IA' + (a^2 - a)\,IC'$$

$$= 1/3\,(\sqrt{3}\,e^{-j30}\,IA' + \sqrt{3}\,e^{-j90}\,IC')$$

$$= J\frac{\sqrt{3}}{3}\,(e^{-j120}\,IA' + c^{-j180}\,IC')$$

$$= J\frac{\sqrt{3}}{3}\,(a^2IA' - IC') \qquad (8)$$

Equation (**8**) may be written

$$IA_1' = \frac{\sqrt{3}}{3}\,e^{j300}\,(IA'\,e^{j30} + IC'\,e^{-j30}) \qquad (9)$$

$$= e^{-j60}\left(\frac{\sqrt{3}}{3}\,IA'\,e^{j30} + \frac{\sqrt{3}}{3}\,IC'\,c^{-j30}\right) \qquad (10)$$

$$Ia_1 = -J\,\frac{IA'}{\sqrt{3}} \text{ from equation (3)} \qquad (11)$$

$$Ia_1 = \frac{-J}{\sqrt{3}}\,e^{-j60}\left(\frac{\sqrt{3}}{3}\,IA'\,e^{j30} + \frac{\sqrt{3}}{3}\,IC'\,e^{-j30}\right) \qquad (12)$$

$$Ia_1 = \frac{1}{\sqrt{3}}\,e^{-j150}\left(\frac{\sqrt{3}}{3}IA'\,e^{+j30} + \frac{\sqrt{3}}{3}\,IC'\,e^{-j30}\right) \qquad (13)$$

$$Im_{a1} = \left(\frac{\sqrt{3}}{3}\,IA' + \frac{\sqrt{3}}{3}\,IC'\right) = \sqrt{3}\,Ia_1e^{j150} \qquad (14)$$

or

$$-Im = \sqrt{3}\,Ia_1\,e^{-j30} \qquad (15)$$

by similar development

$$Ia_2 = \frac{1}{\sqrt{3}}\,e^{j150}\left(\frac{\sqrt{3}}{3}\,IA'C^{-j30} + \frac{\sqrt{3}}{3}IC'\,e^{+j30}\right) \qquad (16)$$

$$Im_{a2} = \left(\frac{\sqrt{3}}{3}\,IA'e^{-j30} + \frac{\sqrt{3}}{3}\,IC'\,e^{j30}\right)$$

$$= \sqrt{3}\,Ia_2\,e^{-j150} \qquad (17)$$

or

$$-Ima_2 = \sqrt{3}\,Ia_2\,e^{+j30} \qquad (18)$$

From equations (**13**) and (**16**) it will be seen that a current proportional to positive or negative phase sequence current can be secured by adding suitable components of current $IA'$ and $IC'$ and passing the resultant through a suitable metering element. Inasmuch as only fractional portions of the $A'$ and $C'$ currents are added to produce either positive or negative phase sequence currents it is obvious that parallel branch or bridge type filters are required. Such a filter is shown in Fig. 6. To secure the proper subdivision of the $IA'$ and $IC'$ currents the elements in the current filter must be properly coordinated.

$$Zp = Zn$$

$$Zz + Zn = (R + Zp)\,e^{j60}$$

Considering only the $IA'$ current flowing in the filter, the current divides, a component $\frac{\sqrt{3}}{3}\, IA'\, e^{j30}$ flows through $R$ and $P$. The remainder $\frac{\sqrt{3}}{3}\, IA'\, e^{-j30}$ flows through $Z$ and $N$.

Considering only the current flow $IC'$ a component $\frac{\sqrt{3}}{3}\, IC'\, e^{-j30}$ flows in $P$ and $Z$, the remainder $\frac{\sqrt{3}}{3}\, IC'\, e^{j30}$ flows in $R$ and $N$.

The resultant current flow in

$$P = \left( \frac{\sqrt{3}}{3}\, IA'\, e^{j30} + \frac{\sqrt{3}}{3}\, IC'\, e^{-j30} \right) = \sqrt{3}\; Ia_1\; e^{j150}$$

The resultant current flow in

$$N = \left( \frac{\sqrt{3}}{3}\, IA'\, e^{-j30} + \frac{\sqrt{3}}{3}\, IC'\, e^{+j30} \right) = \sqrt{3}\, Ia_2\, e^{-j150}$$

A filter is thus produced that permits simultaneous indication of currents proportional to positive and negative sequence currents in the leads of the supply circuits. Zero phase sequence current being eliminated by the use of cross connected current transformers.

The elements $P$ and $N$ may be any form of relaying or indicating apparatus providing the fundamental relationship of $Z_s + Z_n = (R + Z_p)\, e^{j60}$ is maintained.

The magnitude of positive or negative phase sequence current indicated in branches $P$ and $N$ respectively is $\sqrt{3}$ times the actual sequence component in the line conductor and is displaced by 150 or 30 deg depending upon physical connections. In relaying or metering circuits both magnitude and angular relationship must be properly related to secure proper indications.

## Discussion

For discussion of this paper see page 626.

# A Sequence Relay for Network Protectors

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Associate, A.I.E.E. Non-member

PROTECTORS on many low-voltage distribution networks of today operate needlessly several thousands of times each year due to current reversals caused by regenerative loads and difference in loading at various points in the network. Such reversals can be permitted without tripping the protectors and yet maintain a desirable selective tripping characteristic by use of a phase sequence scheme of relaying devised by Messrs. H. R. Searing and R. E. Powers. It employs the fact that practically all power reversals, other than fault conditions, are inherently balanced and that operation of a directional relay can be easily initiated by simple switching operations which draw negative phase sequence currents from the network.

The sequence relay which has been designed in accordance with their theory, and described in this paper, performs the dual function of phasing and tripping. Its operating characteristics, as shown in Fig. 1, are suited to application on low-voltage distribution systems in general.

## CONSTRUCTION

Structurally the sequence relay consists of a single induction-disk directional element, and two over-current elements energized through suitable current and voltage filters. The relay, with the exception of two resistors and a phasing lamp, is mounted within a standard network relay case as shown in Fig. 2. The schematic diagram, Fig. 3, indicates the various elements of the relay and the circuits employed. The control circuit, which is not shown, is energized through contacts on the directional element.

## POTENTIAL FILTER

The potential filter consists of an autotransformer and a reactor, mounted in the base of the relay, and an external resistor. Composite diagrams, Figs. 4, 5 and 6, illustrate the operation of this filter under balanced and unbalanced conditions, and show that the relay voltage obtained is proportional to the positive phase sequence voltage of the system and removed from it by a constant angle.

The reactor-resistor combination, connected across $E_C$ in Figs. 4, 5 and 6, has an impedance angle of 60 deg. The autotransformer is tapped at approximately its midpoint. It will be noted that the open circuit relay voltage obtained, $E_R$, is equal to the vector sum of the voltage rise through the resistor and the induced voltage in the autotransformer. It is proportional to the positive phase sequence voltage $E_{a1}$ of the distribution network and leads it by 120 deg.

The magnitude of the open-circuit relay voltage $E_R$ is determined by the ratio $(N)$ of the external resistance to the sum of the external resistance plus the a-c resistance of the reactor.

$$N = \frac{R}{R + r} \qquad E_R = N\sqrt{3}\,\frac{E_{A1}}{2}$$

$R$ = external resistance
$r$ = a-c resistance of the reactor.

The current in the potential circuit will lag the open-circuit potential coil voltage by an angle that is a function of the series impedance of the potential coil and voltage filter.

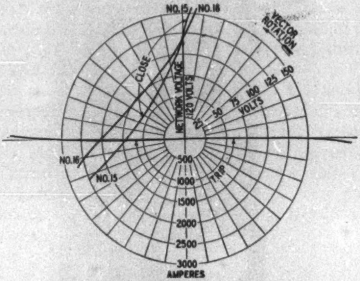

FIG. 1—OPERATING CHARACTERISTICS OF TYPE CN-S NETWORK RELAY STYLE N630355. SERIAL1171632

Assuming balanced three-phase conditions 1,600-ampere current transformers 1,600-5 ratio

$Z_F$ = equivalent impedance of voltage filter

$$Z_F = \frac{R}{4}\,(4 - N + j\sqrt{3}N)$$

For accurate measurements of positive phase sequence voltages the resistance of the autotransformer winding must be kept relatively small.

## CURRENT FILTER

The current filter illustrated in Fig. 7 consists of the current coil of the directional element and a contactor type positive phase sequence current relay connected in series $Z_1$, a reactor $Z_2$ and a negative phase sequence current relay of contactor type $Z_3$, all mounted within the main relay case. An external resistor $Z_4$ completes the bridge type filter. Four current transformers, cross connected, in Fig. 3, to eliminate zero phase sequence currents from the relay, are used to energize the current

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†Westinghouse Elec. & Mfg. Co., Newark, N. J.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

filter. Vector diagrams in Figs. 8, 9 and 10 indicate its operation under various conditions.

The currents $I_C'$ and $I_A'$ from the cross-connected current transformers pass through the current filter as indicated in Fig. 7. Current $I_C'$ divides into equal parts ($I_W$ and $I_X$) separated by a phase angle of 60 deg as shown in Figs. 8, 9 and 10. Current $I_A'$ divides in a similar manner into $I_Y$ and $I_Z$.

The positive phase sequence vector diagram illustrated in Fig. 8, shows the currents through $Z_1$ ($I_X$ and $I_Y$) adding to give a positive phase sequence relay current $I_R$ equal to the $\sqrt{3}$ times the positive phase sequence current of the distribution network and leading it by 150 deg. The currents through the negative phase sequence relay $Z_2$, ($I_W$ and $I_Z$) are equal and opposite and therefore cancel.

Fig. 2

In the negative phase sequence diagram, Fig. 9 which illustrates conditions obtained when phases $B$ and $C$ are interchanged, the current vectors $I_X$ and $I_Y$ which pass through the positive phase sequence relay cancel. Current vectors $I_W$ and $I_Z$ which pass through the negative phase sequence relay add up to equal the $\sqrt{3}$ times the negative phase sequence current of the system.

Inspection of the unbalanced current vectors in Fig. 10 again show the positive phase sequence relay current to be the $\sqrt{3}$ times the positive phase sequence current in the system and leading it by 150 deg. The negative phase sequence current present in the system condition illustrated is also shown. As only positive phase sequence current is used in the directional element of the relay, we are not interested in the phase position of the negative phase sequence current.

Addition of current and voltage vectors representing these unbalanced systems, chosen at random, indicate, as has been proven mathematically in other papers, that these filters will produce currents and voltages that are proportional to the positive or negative phase sequence quantities existing in the system from which they are energized. The series impedance of the voltage filter and potential coil is designed so that these elements can be combined to obtain the sensitive watt characteristic needed in the directional element.

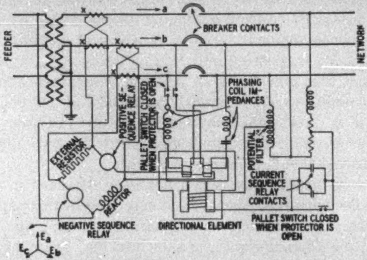
FEEDER
NETWORK
a
b
c
x
BREAKER CONTACTS
POSITIVE SEQUENCE RELAY
PALLET SWITCH CLOSED WHEN PROTECTOR IS OPEN
PHASING COIL IMPEDANCES
POTENTIAL FILTER
EXTERNAL RESISTOR
REACTOR
CURRENT SEQUENCE RELAY CONTACTS
NEGATIVE SEQUENCE RELAY
DIRECTIONAL ELEMENT
PALLET SWITCH CLOSED WHEN PROTECTOR IS OPEN
$E_a$
$E_c$
$E_b$

Fig. 3—Schematic Diagram of a Sequence Relay for Distribution Networks

The dual sensitive, non-sensitive relay characteristic is obtained by the combined operation of the directional element and over-current elements. Parallel connection of the positive and negative phase sequence current element contacts in the potential coil circuit serve to deenergize the potential coil during normal conditions. Operation of the directional element for the tripping function is initiated by action of either or both of the over-current elements. A short time delay is obtained between closure of the current element and directional element contacts, since this contact is held open by spring tension. This interval need be no greater than the operating time of present network relays, yet serves

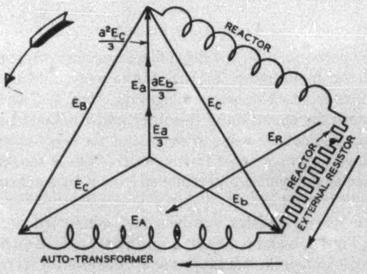
$\frac{a^2E_c}{3}$
$E_a$
$\frac{aE_b}{3}$
$\frac{E_a}{3}$
$E_B$
$E_c$
$E_R$
$E_C$
$E_b$
$E_A$
REACTOR
REACTOR
EXTERNAL RESISTOR
AUTO-TRANSFORMER

Fig. 4—Positive Phase Sequence Voltage Diagram

to prevent tripping the protector by sudden applications of load on the secondary network.

By setting the positive phase sequence element to pick up at currents up to 100 per cent of protector rating, balanced power reversals of that magnitude can be permitted. Negative phase sequence current settings are made relatively low so that sensitive operation of the directional element can be initiated by small magnitudes of negative phase sequence current.

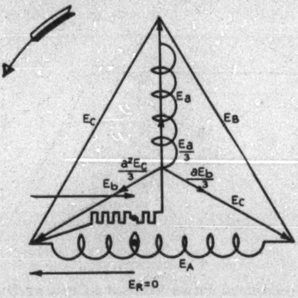

Fig. 5—Negative Phase Sequence Voltage Diagram

It is of importance to note that sensitive operation of this relay may be obtained at all times by permanently closing the contacts of either or both current elements, if the insensitive reverse current characteristic is not needed and a negative phase sequence current source is not readily available. When this is done, the relay functions as a sensitive positive phase sequence directional element and can be used to replace the present sensitive relay.

In order to obtain a clear picture of the relay operation, it may be assumed that balanced three-phase power is being fed in the reverse direction through the protector. All pallet switches in Fig. 3 are open since the protector is closed. The potential coil of the directional element is deenergized and the relay trip contacts are held open by spring tension, as negative phase sequence current is not present and the positive phase sequence current is not of sufficient magnitude to close the current element contacts. Now assume an assymetrical fault in the network, similar to that shown in Figs. 6 and 10. The moment the fault occurs, positive and negative phase sequence currents appear in sufficient magnitude to close the sequence element contacts, energizing the potential coil. Since the fault is in the network the directional element tends to swing its contacts toward the closed position and tripping of the protector is thus prevented. Had the fault occurred in the feeder cables, operation would have been the same except the relay contacts would have swung from the closed to the trip position and opened the protector.

## Phasing Circuit

The phasing characteristic illustrated in Fig. 1 will prevent pumping of non-sensitive relays on low-voltage distribution networks and is sufficiently limiting in its operating range to be satisfactory for many sensitive relay applications. In addition to checking the magnitude and phase position of the feeder voltage, the relay will not close if any of the feeder cables are interchanged and energized.

The phasing circuit consists of two separate coils of high impedance mounted separately over the directional element current coils. One coil is connected in series with a saturating reactor and capacitor, across the breaker contacts in phase *B*. This circuit is near resonance during normal conditions to provide ample torque for low phasing voltages. The second coil is connected across the phase *C* breaker contacts in series with a tapped reactor and a phasing lamp. The phase angles of these circuits are such that the currents in the two circuits are approximately 180 deg out of phase under normal voltage conditions. The resulting field of flux is as in a conventional circuit. When excited with high voltages, as encountered during cross phase conditions, the impedances increase to limit the current and phase angles change so as to obtain opening torque and prevent damaging the protector by faulty closing. Vector diagram, Fig. 11, illustrates the operation of this circuit.

The tap on the phase *C* reactor serves to shift the relay closing curve, as indicated in Fig. 1, to prevent pumping if the system impedance angle will not permit use of the lagging closing curve.

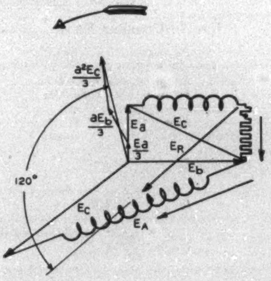

Fig. 6—Unbalanced Voltage Diagram

## Operating Experience

Ten experimental relays, with the current element contacts connected directly in the trip circuit rather than in the potential coil circuit as just described, were mounted on 500-ampere network protectors and installed on a 13.8-kv feeder of the United Electric Light & Power Company's system, April 11, 1931. All transformer banks connected to the feeder, which was 2.8 miles long, were of 150-kva rated capacity.

A general comparison of the operations of network protectors equipped with these sequence relays with the operations of protectors equipped with standard insensitive network relays installed previously at the same locations showed that the operations were reduced on the average only 40 per cent.

On blocking open the negative phase sequence current element contacts, it was found that further reductions in operations on the average of 90 per cent were obtained. The settings of negative phase sequence current elements were subsequently increased from 5 per cent of the protector rating to 8 per cent. The positive phase sequence current element setting at 50 per cent of the protector rating was not changed. While an improvement in the operation of the relays was affected, the results were not satisfactory.

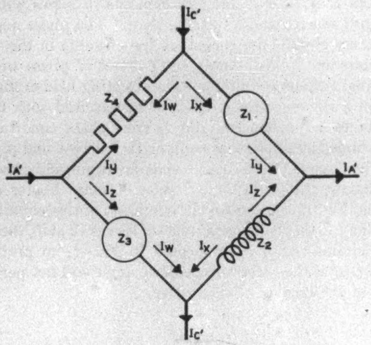

FIG. 7—CURRENT FILTER

$$Z_1 = Z_3$$
$$Z_1 + Z_4 = (Z_2 + Z_3)\epsilon^{-j60}$$
$$I_{C'} = Ib - Ia = Iw + Ix$$
$$I_{A'} = Ic - Ib = Iy + Iz$$
$$Iw = \frac{I_{C'}}{\sqrt{3}}\epsilon^{j30}$$
$$\left.\begin{matrix} Ia \\ Ib \\ Ic \end{matrix}\right\} = \text{Line currents}$$
$$Ix = \frac{I_{C'}}{\sqrt{3}}\epsilon^{-j30}$$
$$Iy = \frac{I_{A'}}{\sqrt{3}}\epsilon^{j30}$$
$$Iz = \frac{I_{A'}}{\sqrt{3}}\epsilon^{-j30}$$

From observations made, it was found that the current elements were causing the protectors to trip on suddenly applied secondary loads when the directional element trip contacts were held closed by power reversals. It should be remembered that the contacts of the current elements, in these experimental relays, were in series with the "trip" contacts of the directional element. Thus on the occurrence of an unbalanced secondary load, the negative phase sequence current element picked up, and since the directional element "trip" contacts were closed by the reverse power flow, the protector opened. The current elements, which are practically instantaneous, picked up before the directional element, which tended to close on the secondary load had time to open its "trip" contacts, thus completed the trip circuit. Large unbalanced secondary loads suddenly applied produced similar operations with the positive phase sequence current element picking up.

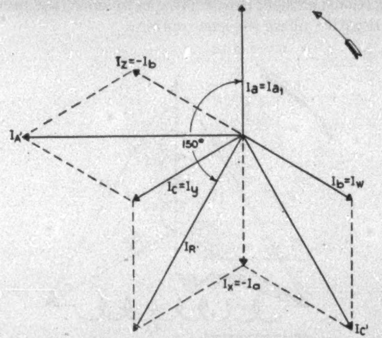

FIG. 8—POSITIVE PHASE SEQUENCE CURRENT DIAGRAM

$$I_R = Iy + Ix = \sqrt{3}\, Ia_1\, \epsilon^{j150}$$
$$I_N = Ia_2 = Iw + Iz = 0$$

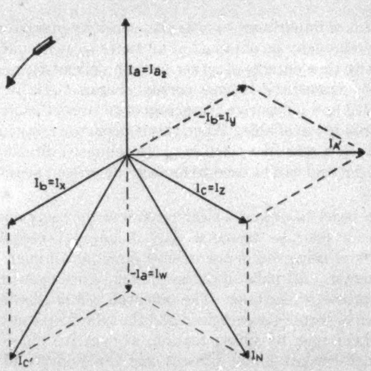

FIG. 9—NEGATIVE PHASE SEQUENCE CURRENT DIAGRAM

$$I_N = Iz + Iw = \sqrt{3}\, Ia_2\, \epsilon^{-j150}$$
$$I_R = Ix + Iy = 0$$

To remedy this condition, the contacts of the current elements of the ten sequence relays were connected in series with the potential coil of the directional element as shown in Fig. 3. With this arrangement, the directional element "trip" contacts were normally opened and thus when either of the current elements picked up on a secondary load, the "trip" circuit could not be completed, as the disk of the directional element tended to rotate further in the "close" direction.

The network protectors equipped with these experimental sequence relays have been used at several other locations, since their initial installation, in order to obtain operating experience under all possible system conditions. Locations were selected where frequent and large reversals of power occurred due to elevator regeneration or other conditions. Satisfactory operation of all protectors was experienced at every location.

The operating record of the protectors now in service is tabulated below. The list includes all operations due to cable faults, interruption of the feeder at its source, and power reversals in excess of relay settings.

| Feeder voltage (kv) | Period (days) | Total operations for period | Average operations per day |
|---|---|---|---|
| 13.8 | 262 | 21 | 0.08 |
| 13.8 | 135 | 64 | 0.50 |
| 13.8 | 173 | 10 | 0.06 |
| 13.8 | 175 | 24 | 0.14 |
| *13.8 | 124 | 207 | 1.70 |
| 13.8 | 168 | 20 | 0.12 |
| 13.8 | 108 | 49 | 0.50 |
| 13.8 | 265 | 7 | 0.03 |
| 3.0 | 179 | 1 | 0.006 |

*Graphic meter records have shown that frequent power reversals of long duration occurred at this location. Current magnitudes in excess of the relay settings caused the large number of operations noted. These operations have been practically eliminated by readjusting the current elements so that they do not pick up on the current magnitudes normally encountered at this location.

Twenty-nine faults have been experienced on feeders on which network protectors equipped with sequence relays were installed. The operation of the sequence relays on each fault was correct.

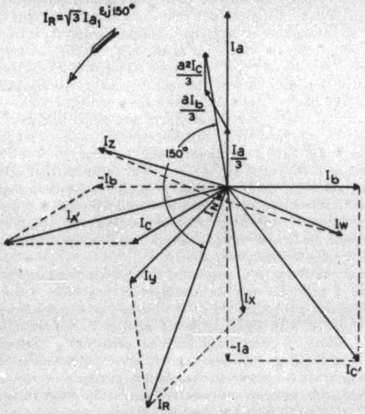

Fig. 10—Unbalanced Current Diagram

Seven 1,600-ampere and four 3,000-ampere network protectors equipped with sequence relays have been installed recently; while eleven 1,600-ampere and five 3,000-ampere protectors with sequence relays will be installed at an early date.

## Tests

Several tests were made to determine the ease with which the ten protectors equipped with sequence relays could be opened after deenergizing the 13.8-kv feeder at the power station. These tests were made on the initial installation when all protectors were connected on one feeder.

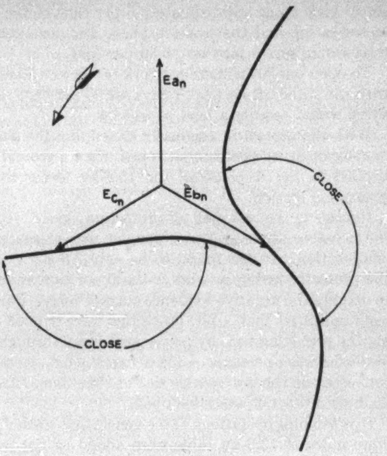

Fig. 11—Operating Characteristics of the Separate Phasing Coil Circuits

Closing torque is developed within a given circuit when the associated feeder voltage terminates within its closing area. The resultant torque is always in the "opening" direction when feeder cables have been incorrectly connected as indicated above:

DELTA-STAR SYSTEMS

| Feeder cables interchanged | Feeder voltage | | Direction of torque | |
|---|---|---|---|---|
| | $E_b$ 180° from | $E_c$ 180° from | Phase *B* | Phase *C* |
| *a* and *b* | $Ea_n$ | $Ec_n$ | Strong open | Strong open. |
| *b* and *c* | $Ec_n$ | $Eb_n$ | Light closing | Strong open. |
| *a* and *c* | $Eb_n$ | $Ea_n$ | Strong open | Fair closing |

With all cables rotated 120° or 240°, both phases will produce opening torque.

If feeder voltage $Ea = 0$, the protector cannot close as the control circuit is connected across phase *A-C*.

STAR-STAR SYSTEMS

When any two feeder cables, other than phase *a* and ground, are interchanged and when all cables are rotated 120° in either direction opening torques will be developed in the relay. When phase *a* and ground cables are interchanged, the low control voltage obtained prevents closing of the protector

Two methods of creating a negative phase sequence current were used:

1. A single-phase load on the secondary side of one distribution transformer bank.
2. Grounding one conductor of the 13.8-kv feeder at the station which causes an unbalance in the charging current.

Using a load connected from *C* phase to ground on the secondary side of 150-kva distribution transformer bank, it was found that a load of approximately 500 amperes at 85 deg or 5.2 kw was required to open the ten protectors on the feeder. Inspection made after the station breaker was opened but before the secondary load was applied showed that no protectors opened previous to applying the load. At the time of the above test, the negative phase sequence current relays were set to pick up at approximately 5 per cent of the protector rating and the positive phase sequence current relays were set to pick up at 30 per cent.

To open ten 500 ampere network protectors equipped with the standard network relays set 30 per cent insensitive would require a load of 540 kw.

With the protectors originally closed and the station breaker open, all protectors tripped when a ground was applied to the *A* phase of the 13.8-kv feeder at the generating station.

Repeating the test with all protectors blocked closed, the negative phase sequence current was measured at one location. It was found to be only 2.9 per cent of the protector rating instead of the 5 per cent required to operate the negative sequence current relay. Further tests indicated that a few protectors were tripped during the preceding test, by power exchanges through the feeder between portions of the network which were not connected on the low voltage side at that time. The remaining protectors cascaded open.

By switching operations at the generating station, five more miles of 13.8-kv cable were added to the feeder without increasing the connected transformer capacity.

After blocking the protectors closed and grounding the *A* phase of this longer feeder, the negative phase sequence current was again measured at the above mentioned location and was found to be 8 per cent of the protector rating, which was ample to operate all negative phase sequence current relays.

Back feed tests on the long 13.8-kv feeder showed that all protectors other than those feeding back remained open and the relays had strong opening torques. Transformer voltages on some protectors as high as 133 volts were obtained during this test.

Complete laboratory tests and operating experience have shown that needless protector operations are practically eliminated by use of this relay. Decreased likelihood of light flicker and reduced wear on the protector result from keeping protectors closed a greater proportion of time than heretofore. Load-back methods of clearing feeders, equipped with insensitive relays, and the resulting disturbances in the network are also avoided. These advantages have been obtained in a single relay, without sacrificing the accurate phasing and tripping characteristics now considered essential to the successful operation of the network protectors.

The authors wish to express their thanks to Messrs. H. R. Searing, R. E. Powers, B. E. Lenehan and C. T. Altfather, whose work has added materially to this paper.

## Discussion

### APPLICATION OF PHASE SEQUENCE PRINCIPLES

(Searing and Powers)

### A SEQUENCE RELAY FOR NETWORK PROTECTORS

(Orcutt and Bostwick)

**W. J. McLachlan:** The desirability of a relaying scheme for network protectors which will result in the elimination of unnecessary operations, with minimum sacrifice in system operating flexibility, has been evident from operating experience in certain systems. These papers present a very interesting approach to this problem.

To the uninitiated the statement that the average number of operations is at the rate of 3 to 5 thousand annually per protector, may be unduly alarming. It should be particularly noted that this statement is qualified as existing "in certain locations." These locations have been generally limited to large metropolitan systems where multiple supply is from several sources, network load is relatively light, and elevator regeneration is frequently encountered. The average annual operating rate in locations other than these is but a fraction of these values. An understanding of this fact is important in evaluating the advantage of a relaying scheme which reduces the operating rate, as opposed to any possible disadvantages in specific applications.

Among the methods cited for obtaining negative sequence current to cause the protectors to be opened is that of earthing one conductor of a delta-connected feeder which has been disconnected from the source. This method will not be found to be applicable in systems on a general scale. Systems with long 22-kv and 27-kv feeders have found it necessary to employ shunt reactors to neutralize cable capacitance, thus limiting the voltage rise on the network and feeder when the feeder is energized only from the network. A recent development in these devices incorporates grounding transformer action of benefit in limiting the flow of charging current under the earthed conductor condition. The action of this device is such that with certain values of cable capacitance no negative sequence current flows from the network when one conductor is earthed. From the tests reported, 7.8 miles of 13-kv cable were required to give 8 per cent negative sequence current through 10—500-ampere protectors on 150-kv banks. Had this feeder been arranged with its full capacity in connecting transformers and all of the associated protectors equipped with sequence relays, the cable length required would have been approximately 4 times as long; 13-kv feeders of such length are rare. It will be found that a feeder having sufficient cable capacitance to give 8 per cent negative sequence current under the earthed conductor condition through all connected transformers, of ratings now in use, will give rise to objectionable overvoltage conditions when the cable is energized through one transformer only.

From the above, it is concluded that the earthing of one conductor is practical only as a temporary expedient where few transformers are connected to the feeder—or where a few only are equipped with phase sequence relayed protectors. In the consideration of general applications, some other controllable source of negative sequence current must be included. Inasmuch as it will be desired to clear feeders in which one conductor has faulted to ground, such controllable source must have sufficient capacity to give the desired minimum negative sequence current, when that existing due to a ground on any phase of the cable is added vectorially to the output of the source. This may require a considerable increase in the capacity of the source over that required to give operation with the cable ungrounded, inasmuch as the negative sequence current due to the unbalanced cable capacitance may be opposite in phase to that of the source.

A second method of obtaining negative sequence current, illustrated in Fig. 5 of the paper by Mr. Searing and Mr. Powers, is described as a small motor-generator set. It is true that the generator of this set may be small—but not the motor. This motor must carry the total negative-phase current and withstand full voltage. Assuming a 10,000-kva 27-kv feeder, with 8 per cent negative sequence current required, this amounts to 800 kva.

Load-back methods of tripping insensitive network relays do not necessarily impose an objectionable voltage disturbance on the network. This may be accomplished without appreciable disturbance by imposing means for circulating current through the feeder to be cleared and the remainder of the system. Generally, such a method will result in less disturbance when one protector only has not opened than any of the methods of imposing negative sequence current which have been mentioned in these papers.

Objectionable unnecessary operations of protectors can be eliminated by the use of non-sensitive relays. Feeders can be cleared without objectionable disturbance when such relays are used. The comparative merit of the sequence relay in cases where the reduction of protector operation is desirable, must therefore be judged on the basis of overall system economy, including load-back means for either scheme, reliability of the relay equipment, and maintenance requirements.

From the practical viewpoint, an objection to this scheme of relaying may arise from the fact that a multiplicity of electrical devices is involved, the failure of any one of which will render the relay completely inoperative either in tripping or closing operation or both. This is contrasted to the more usual relaying methods in which the actuating elements operate in accordance with single-phase phenomena, such that the failure of a single part affects only the operation of the corresponding phase element.

In the arrangement as described, the directional element must operate on the same exacting requirements of current magnitudes and phase angles as the present sensitive relays. Such requirements have been a decidedly limiting factor in the design of network relays. Because of the range of current on which operation is desired, the relay must operate on small torques, with corresponding limitations in sturdiness and overall reliability of the devices. A relaying system which does not impose these stringent requirements would be of obvious advantage. In the sequence relay, the tripping phase angle characteristic is dependent not only on the characteristics of the directional relay elements but also on the exact characteristics of all devices in and associated with the filter circuits. Extreme care must be exercised in the design and manufacture of this equipment to control exactly the characteristics of all devices, or variation in the tripping characteristic will result in failure to meet the requirements.

**J. A. Brooks:** In general the history of development has been that some anticipated conditions do not materialzie and other conditions not anticipated become a problem. In addition some parts of the new device are usually obtained by use of standard equipment developed before for other applications and not particularly suitable for the new functions desired. I believe that our existing low-voltage a-c network protector has not escaped these more or less traditional fates and that we should now carry out the third historical phase of development by materially simplifying the device originally developed. These papers are unquestionably a forward step in this direction.

In the past, manufacturers have been somewhat handicapped by the many requirements specified by the operating companies for network protector operation. In brief these requirements have been that the network protector shall not close unless the feeder voltage is at least equal in magnitude to network voltage, unless the feeder voltage is in phase with or slightly leading the network voltage, and unless the phase rotation of the incoming feeder is the same as that of the network. The opening requirements have specified that the network protector shall not open unless polyphase power is flowing from the network to the feeder and that it shall be possible to adjust the tripping device for operation on magnitudes of backfeed varying from the excitation energy of the associated network transformer to the short-circuit currents and power factors obtainable for all possible network constants. As pointed out by Messrs. Searing and Powers the requirement of sensitive reverse power trip has materially complicated present network relaying equipment, this complication being necessary to prevent pumping operations and to make the sensitive feature operable on the leading backfeeds sometimes drawn by high voltage network feeder cables. The introduction of the phase sequence relay provides a new means for handling these difficulties.

The network relays and network switches used in the present network protectors are fundamentally of the same design as switchboard devices used for several years before the advent of the low voltage a-c network. Switchboard application is different from network application in that a switchboard device can be inspected and maintained easily whereas a distribution device housed in a water-tight compartment located in a street manhole is not readily accessible for inspection and maintenance, also that the number of such distribution devices on a large system will become so great as to make frequent inspection and maintenance a large item. Before the advent of the network protector, distribution devices consisted chiefly of distribution transformers and cable, both of which require relatively little maintenance. The network protector to be entirely satisfactory should be made to approach this ideal as far as possible.

These two papers pertain only to the relay equipment and not to the network switch which also is a source of inspection and maintenance expense. I believe the fact that fuses are now almost universally used as back-up protection indicates that the industry is not satisfied that the present network protector is sufficiently sturdy and reliable to be counted upon for positive operation. There are several undesirable features introduced by the use of the back-up fuse, the chief of which are a material increase in the loss dissipated in submersible network equipment and the use of a straight overload device in series with an elaborate directional device. The elimination of the fuse should make it possible to use smaller subway type network protectors for a given rating and should eliminate troubles which arise in certain service layouts due to the lack of fuse selectivity.

It would seem that the only urgent requirements of operation for network protectors are that they close when and only when the conditions on the associated feeder are normal or when the voltage on all three phases of the feeder exceed a pre-determined value, that the network protector should trip when and only when there is a short circuit on the associated network feeder or a means is applied at the station for opening all network protectors on a feeder. Additional operating requirements may be desirable but a careful analysis of their justification should be made if their use adds complication.

Transmission systems have for a long time been networks of varying extent. They have in most cases been operated by closing all the switches and leaving them closed except when equipment was taken out of service for inspection and repair or when a fault on a part of the system was isolated by relay operation. This method of operating is predicated on the premise that the system must be designed and operated in such a manner that abnormal feeder conditions, except in cases of emergency, will not occur, and usually when such emergency conditions arise it is not intended that more switches in the transmission system open than is required to isolate the trouble. Is there any reason why the operation of the distribution network should be different from the above except that a means be added for voluntary opening of the network switches from the station?

In my opinion the manufacturers of network protectors should develop an entirely new equipment, the relay and switch both designed to go together as a unit, both being as simple, sturdy and reliable as it is possible to make them, this reliability being great enough to allow abandonment of the fuse and the simplicity being sufficient to allow an appreciable reduction in price. The operators should cooperate to the utmost in this development and eliminate all past operating requirements which cause inherent complication in the network protector and which are not absolutely necessary for satisfactory system operation. This development should not be influenced by past prejudices on the part of either the manufacturer or operator, and all component parts of the equipment should be designed and built for distribution application which requires a very minimum of inspection and maintenance and a very maximum of reliability.

**W. R. Bullard:** The method of relaying described in these papers solves, in a very ingenious manner, certain operating problems that have arisen in connection with low voltage a-c networks. This method of relaying, undoubtedly, has its fields of application, probably the major field being that of large networks in metropolitan areas. I believe, however, that the general situation should be very carefully studied before any move is made to make a general change in design of network protectors by incorporating this principle. One thing which should be considered is the fact that many small operating companies are meeting the problems mentioned in these papers satisfactorily with existing equipment. These companies have organizations trained in the use of present equipment and any general change of design would mean considerable inconvenience, both in the problem of stocking apparatus and in the matter of training the personnel to handle the new design.

A number of years ago I wrote a paper outlining my standpoint as of that time concerning operating requirements of network relays. The requirements outlined were rather exacting and complicated. Since that time much has been learned about the operation of networks and some of the anticipated applications of the network principle have not materialized. One of these is automatic synchronization at the load. The present business situation has been a vital factor in revising many engineering standpoints and we have learned, among other things, that many operating conveniences, formerly considered justified, can be properly and economically dispensed with. Another factor in this specific problem is the growing interest that is being shown in the application of low voltage networks to overhead distribution systems which focuses attention on the desirability of low cost and extreme simplicity. In view of all these factors, I now feel that the past tendency in the development of network equipment has been to attempt to make it perform too many functions, and that this tendency has resulted in too many mechanical and electrical complications. Therefore, if any general change is to be made in network apparatus design, I feel that it should be directed toward general and complete simplification. The method of relaying described in these papers is a step toward simplification, but stops considerably short of the goal I have in mind.

One of the present factors which tends to prevent the accomplishment of really worth while simplification is the requirement for high sensitivity, both in the opening and the reclosing functions. If this requirement were dispensed with or materially modified, it seems quite probable that a large percentage of the complications involved either in present equipment or in the method of relaying described in these papers would be eliminated, the result being an extremely simple and sturdy piece of equipment, possibly lacking sensitive relays of any kind, but utilizing instead the direct application of control impulses to the switch mechanism itself. Perhaps, we are not yet prepared for a sweeping change of this kind, but I have a feeling that it will eventually be brought into the general picture. In the meantime, it would seem desirable to avoid any wide spread intermediate change of design in the face of the need for a more sweeping change.

**H. C. Forbes:** Messrs. Searing and Powers point out in their paper several cases where the electrical relationships on the system under what they very properly describe as normal operating conditions may be such as to produce an excessive number of network switch operations. The phase sequence relay which they have developed promises to eliminate the excessive number of operations under these troublesome conditions and since at the same time it introduces other desirable features it will no doubt, receive a royal welcome from the central station industry. This admirable solution of a difficult distribution problem, however, should not be taken by those engineers who are concerned with the design and operation of the system from which the network supply is derived as an occasion to shrug their shoulders and assume that nothing further remains to be done.

On the contrary, the differences in phase angle and voltage which occur on the system at different points still will be present and may manifest themselves in the shape of overloaded distribution transformers and loss in efficiency due to unwanted circulating currents. It is my belief that further effort in the direction of eliminating this trouble at its source would be well rewarded. For example, generating station busses are usually divided into sections which are interconnected by means of reactors or in some cases they may be even more completely segregated by interconnecting them only through system ties and feeders external to the station. Now under such conditions there will assuredly be appreciable differences in voltage and phase angle between the several bus sections in the station unless a definite effort is made to avoid them. I venture to say that in most such stations there are adequate voltmeter installations so that the operators have a satisfactory guide in controlling the voltages but in no station to my knowledge is there a permanent installation of equipment which gives the operators a direct indication of the differences in phase position of the several bus sections. The engineers of the central station companies will do well to give careful consideration to the provision of such facilities. In the meantime the station operators can hardly be severely criticized for not maintaining their bus sections in phase in the absence of any means of knowing definitely when they have accomplished the result.

There are many other ways in which careful design and operation of the power system can supplement the benefits to be obtained from the newly developed relay and there seems no reason to doubt that the improved equipment will go hand in hand with improved engineering coordination of the elements of the central station systems, and that further enhancement of the well deserved popularity of the low voltage a-c network system of distribution will result thereby.

**C. M. Gilt:** The papers presented on phase sequence relays well illustrate the change in thought that frequently accompanies a development of any character. I believe the general application of so-called sensitive network relays has been due to a philosophy of design and operation common during the early stages of the development of the low-voltage, a-c network, but which has not been followed out as operating experience was obtained.

Many of the early ideas were built around the assumption that a successful network required the use of relatively high impedance transformers closely spaced so as to obtain relatively low impedance in the secondary connections between transformers. With such a design proper voltage regulation of the network would be obtained by taking primary feeders and network transformers out of service progressively as the load decreased, so as to obtain approximately constant load on the feeders in service and reduced transformer core losses. Such operation required the use of sensitive relays which would readily trip on exciting current of the network transformer or the charging current of the high-tension feeder when backfed from the network.

As a matter of actual development, networks are commonly built with transformers of normal reactance design and spaced far enough apart so that there is usually a fair amount of impendance between units. The primary voltage is regulated according to load so as to obtain approximately constant voltage on the network, and feeders and transformers are not taken out of service at periods of light load for the sake of regulation or saving of losses. Consequently, one of the principal incentives for the use of sensitive relays has disappeared or never actually developed. Furthermore when it does become necessary to connect two or more network transformers with relatively low impedance between them, the sensitive relay becomes a real handicap in that it trips units on small backfeed due to slight differences in feeder voltages at time of light load and so reduces the transformer capacity that bad flicker and frequent network switch operations result when large motors are started or elevators are operating.

By removing the requirements for sensitive operation, it would appear possible to eliminate other requirements and to simplify greatly the network relays, securing a much more sturdy device that will not require the delicate settings and adjustments of the present relays. It is of course essential that the network switch should trip promptly on high tension feeder failure and that means should be provided for readily tripping the breaker on the few occasions that it is necessary to take the high tension feeder out of service for maintenance or rearrangements.

It would appear that the relay characteristics outlined in these papers provide one method of eliminating the sensitive characteristics of the standard relay, while still retaining the essential features of tripping on high tension feeder failure and providing a means of intentionally tripping the breaker when such needs arise.

It is highly desirable that developments with these objects in view be carried along and particularly it is to be hoped that we may obtain still further improvements in simplicity, sturdiness and reliability of network switches and relays.

**H. R. Searing and R. E. Powers:** Simplification in apparatus ordinarily is accomplished through the reduction in actual requirements in the number of functions performed by the apparatus and a reduction of functions performed must be in order before a more simple device can be produced. With increased operating experience in secondary network systems it is apparent that considerable thought is being devoted to the network protector with the general thought of "laying down the bars" on requirements to secure a more simple unit. This thought applies to future devices not designed at the present time; however, we have many thousands of network units in service today and changing conditions make it necessary to render a large number of these units selective, tripping only on power reversals on the order of 20-100 per cent of bank rating. Negative phase sequence auxiliaries can be added to existing equipment to produce results comparable to that secured from the relays described in this paper, the directional function being performed by the existing three-phase watt element. It is the general feeling that any system operated selectively will require some form of load back method to open protectors from the source. The system employing negative phase sequence current in conjunction with a directional watt element in comparison to the existing proposed schemes will require a minimum amount of terminal apparatus to provide the necessary intentional tripping functions.

With reference to the discussion by Mr. W. J. McLachlan we agree that earthing of a single conductor on a delta-connected feeder which has been disconnected from the source is not a universal solution in providing a source of negative phase sequence current for tripping. In the body of our paper we point out that the quantity of negative sequence current is a function of cable length, voltage and number of banks involved and is thus a variable quantity. In referring to Fig. 5 of our paper Mr. McLachlan calculates 800 kva for the motor of the motor-generator set to accompany a 10,000 kva 25 kv feeder. In considering that particular feeder combination equipped with selective equipment of standard design set at 25 per cent power reversal it would require at least 2,500 kw transfer to cause the protectors to open, and if the current circulated were other than at unity power factor the kilovoltamperes would be greater. Thus relatively the motor-generator set can be classified as small although there will be a difference in the rating of motor and generator. Static apparatus can be employed as a means of providing a source of negative phase sequence current for tripping and may prove to be superior to rotating equipment.

Generally speaking, we intend to use negative phase sequence current to provide an initiating impulse to trip protectors and not to open switches that fail to open mechanically or otherwise.

The only manner in which a protector in that condition can be opened is manually or by opening the associated fuses by the circulation of current through the defective protector and measured at the switch takes, for a 500-kva bank approximately 2,000 kva for a protracted period of time.

Mr. McLachlan states that the directional element of the proposed arrangement is subjected to the same requirements as the present relaying system as far as magnitude and angular relationship are concerned. In the main this is true, however, careful study of field performance shows that the relay has been one of the most reliable and satisfactory portions of the network protector and when properly applied functions satisfactorily. Failures to operate have in the majority of cases been at points other than the relay.

We have encountered no difficulty whatsoever in designing relay and associated filter so as to secure the proper relay characteristics with ordinary shop testing and routine.

**H. S. Orcutt:** The relay described in our paper was designed to meet all the requirements originally considered as being necessary for successful operation of the network protector. While it may seem that the relay is complicated, as pointed out in the discussion, it is in fact no more so than the present relaying equipment since the majority of its parts are fixed resistors and reactors which have been built with a large factor of safety to avoid failures.

We are in complete agreement with the need of further simplification of the network equipment. It was with this idea in mind that the sequence relay was developed in its present form with a single disk directional element and with the new design of phasing circuit, otherwise a negative phase sequence overcurrent element could have been added to the standard relay equipment and satisfactory results obtained. The addition of a negative phase sequence overcurrent element to the present relaying equipment affords a means of eliminating the manual operation of the present non-sensitive network protectors when it is desired to deenergize the feeder.

With the growing feeling toward simplification many of the exacting characteristics required of the original network relays are decreasing in importance or are being eliminated entirely. This undoubtedly will result in the simplification of the relaying equipment. From operating experience in New York it is found that from 80 to 90 per cent of the failures on network protectors are directly contributable to the breaker. We believe, therefore, that the logical place to start simplification or improvements is on the breaker.

# Higher Steam Pressures and Temperatures

## A Challenge to Engineers

BY MELVIN D. ENGLE* and IRVING E. MOULTROP†
Member, A.I.E.E. Fellow, A.I.E.E.

THE optimum steam pressure and temperature for steam-electric generating stations has not been determined. Because of the importance of the subject to the electrical industry, it has been considered worth while to present a resumé of what has been accomplished with comments of such a nature as to provoke helpful discussion.

Fig. 1 shows the operating pressures and temperatures that have been used in the steam-electric generating stations of one of the electrical companies in the United States from 1885 to date, and Fig. 2 shows the improvement in fuel economy that has resulted from the use of higher steam pressures and temperatures and other improvements in station design in the stations of the same company. These curves are typical of what has been accomplished by the electrical industry in general by constant and persistent study of the problem. The second curve in Fig. 2 shows what has been accomplished by all utility plants in the United States—good, bad, and indifferent. These curves indicate that the fight for better economy has been very much worth while but are at the same time a challenge to the ingenuity of the engineers of the future. This better and better fuel economy has been accomplished in general by stations that have cost less and less per unit of capacity in spite of their better economy. Will the engineers of the future be able to meet the challenge?

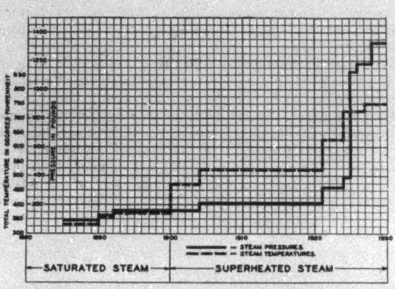

FIG. 1—STEAM PRESSURES AND STEAM TEMPERATURES USED IN THE BOILER PLANTS OF THE EDISON ELECTRIC ILLUMINATING CO. OF BOSTON

Fig. 3 shows a comparison of approximate station heat rates at constant pressure and varying temperature from 750 deg to 1,000 deg F. It shows graphically that no matter what pressure or cycle one may select, the higher the steam temperature, the better the station economy. Most of the problems involved in the use of a steam temperature of 750 deg F have been solved. Some of the new stations now being built will operate at a temperature of from 825 to 850 deg F and within a comparatively few years we will, no doubt, be operating with steam temperatures of 1,000 deg F. The limitations imposed by the materials of construction for superheaters, reheaters, turbines, valves, etc., are slowly being removed and the 1,000 deg F station is no longer a fantastic dream. It will be a reality within the lifetime of many of those living today.

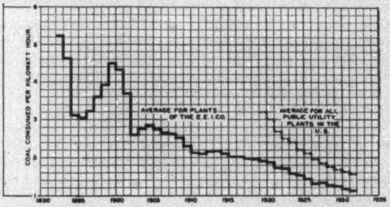

FIG. 2—FUEL CONSUMPTION FOR THE SYSTEM OF THE EDISON ELECTRIC ILLUMINATING CO. OF BOSTON AND ALL UTILITIES IN THE UNITED STATES

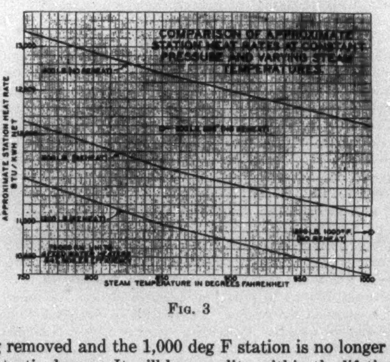

FIG. 3

The problem of the control of the temperature of the steam leaving the superheaters and reheaters is one that must be solved before much further progress can be made, for while we could probably design for nearly 1,000 deg F today, the equipment would not withstand the temperatures that would exist during abnormal operating conditions such as dirty boilers, poor combustion conditions, and changes in the character of the fuel being burned. This problem is being studied and seems well on the way to a satisfactory solution.

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Fig. 4 shows the comparison of approximate station heat rates at constant temperature and varying pressure from 400 lb to 2,500 lb. These curves show that no matter what steam temperature one may select, the higher steam pressures show considerable improvement in station economy when compared with the so-called moderate pressure of 400 lb. The improvement in economy for pressures at least as high as 1,200 lb are of such a magnitude that station designers can not afford to disregard them.

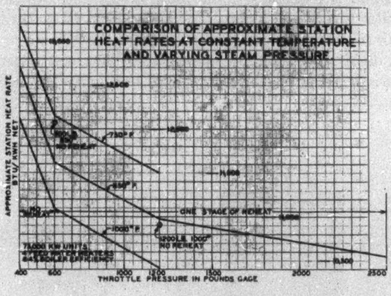


Fig. 4

A number of designers seem to favor a pressure of from 600 to 700 lb and a temperature of from 825 to 850 deg F without reheat on the plea that such a station gives good economy and is simpler than one employing the reheat cycle. It is true that such a station (600-700 lb) will give approximately 5 per cent better economy than a 400-lb 850-deg station but the designer should not overlook the fact that on the same basis a 1,200-lb 850-deg reheat cycle station will give approximately 13½ per cent better economy than the 400-lb 850-deg station.

A number of stations is in service employing the reheat cycle and no very serious operating difficulties have shown up. It boils itself down, therefore, to the question of the unit cost of construction for stations of various pressures and cycles.

It is an extremely difficult matter to determine in advance the exact comparative cost of a new station or an extension to an old station, where the only difference is to be in the steam pressure or steam temperature. The difference in unit cost is a very small percentage of the whole, and an error in design can change the unit cost more than the difference due to pressure or temperature. Those who have actually built stations for moderate and high pressures are not really sure as to the exact difference in unit cost because of the other variables entering into the various designs. However, all of those who have built high pressure stations feel that the higher pressure was justified.

Past experience has shown in general that higher steam pressure does not of itself increase the cost of construction, but actually results in lower unit costs of construction. For example, probably all agree that a 400-lb 750-deg non-reheat station would cost less per kilowatt of capacity than a 200-lb 750-deg station built to operate on the same cycle. It is known, however, that a 600-lb, 750-750-deg reheat station would cost more per kilowatt of capacity than a 600-lb 750-deg non-reheat station.

The probable facts of the case are that the unit cost of construction decreases with increase in pressure as long as the same heat cycle is employed and as long as the pressure does not require a radical change in the design of the pressure apparatus. When a pressure is reached that requires a change in the heat cycle or a radical change in design of the pressure apparatus, the unit cost probably takes a sudden jump and falls off again as the pressure is increased until another change in heat cycle or design is necessary. This idea is illustrated graphically by Fig. 5.

The unit cost of the pressure parts is greater for higher pressure apparatus and so high-pressure mistakes are more expensive than low-pressure mistakes. Our discussion is based on proper design for all conditions.

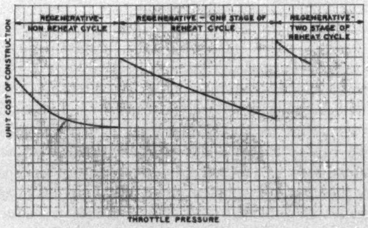


Fig. 5—Probable Variation in Unit Cost of Construction of Steam-Electric Generating Stations at Constant Temperature and Varying Pressure

Fig. 6 shows the additional capital investment per unit of capacity that is justified for a 1,200-lb 750 deg-750 deg reheat station over a 400-lb 750-deg non-reheat station for 40 per cent load factor and various costs of fuel. Where there is a question in one's mind as to the exact unit cost of the high-pressure station it is comforting to know that a considerable increase in unit cost is justified by the higher thermal efficiency.

We are all interested in generating electrical energy for the lowest cost per net kilowatthour. We are also interested in keeping down to a minimum the cost per net kilowatt of capacity of our generating stations. We would be untrue to our trust, however, if we did not design according to our best engineering judgment so as to obtain the lowest cost per net kilowatthour generated. We should endeavor to obtain the highest possible "dollar efficiency."

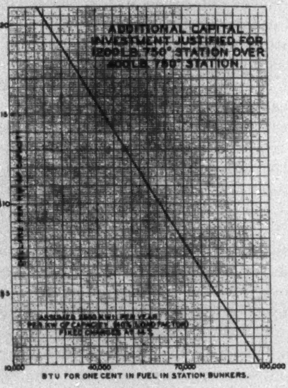


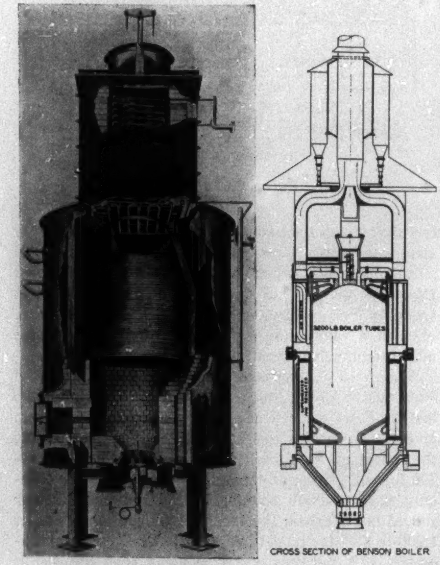
Fig. 6

Another important consideration in the selection of the most economical pressure and temperature is the fact that the design and manufacture of high-pressure generating equipment is in its infancy. As time goes on, designs will be improved and manufacturing methods will be changed so that we will be able to install the more economical equipment for considerably less per unit of capacity than we can today. It is necessary, however, that we go through a period of development. If we can promote this development without actual financial loss, by the use of equipment that is economically justified at its present price, we aid in the progress of the art and will reap even greater profits in the future. If we refuse to install the equipment which our engineering studies indicate is the most economical, we are seriously hindering the progress of our industry.

Station designs in which one steam generating unit supplies all of the steam required by one turbo generator unit are becoming more and more generally accepted as the most economical. A properly designed steam generating unit has about the same availability today as the turbo generator unit and this change in design is both logical and justifiable. Furthermore, since the availability of the steam generating unit and turbo generator unit are about the same, there does not seem to be any justification in a station for spare steam generating units. We can expect the stations built in the future to have firm boiler capacity very closely matching the steam requirements of the turbo generator units at full load.

Welded boiler drums are a new development that will probably become more generally used in the future and should result in lowering the unit cost of the steam generating units.

Boiler manufacturers have only recently made any serious attempts to determine the maximum safe capacity of the boilers which they manufacture. This information is necessary if the most economical design of boiler is to be obtained. The boiler units of the future will probably be designed to operate the boiler proper at nearly its maximum safe capacity and heat traps of various kinds will be so arranged as to give the boiler room efficiency that is justified under the particular conditions of the installation.



A B

Fig. 7—Cross Section of Experimental Series Boiler at Purdue University and Benson Boiler Installed in Europe

Where it is possible to use it, we should not forget that the most economical boiler design is one using the longest drums that it is possible to obtain and the longest tubes that will fit in with the particular design. Such a design not only results in the lowest cost of the boiler itself but also gives the lowest unit cost of building and furnace and practically all items that enter into the cost of the boiler plant.

The series boiler has been in use for several years in Europe and the manufacturer claims that such a design results in the lowest unit cost. We have recently had considerable interest shown in this type of boiler in the United States, and two experimental units have been built and tested. The possibilities of this type of steam generating unit warrants further study, and probably commercial trial in the United States. In spite of our natural prejudice against the idea in general, and the many reasons we can think of why such apparatus would be unsatisfactory, the facts of the case are, that they are in service in Europe and operating with some degree of success. The series boiler and superheater may be the answer to our need for superheat control for higher temperatures and may have possibilities that we do not realize at this time.

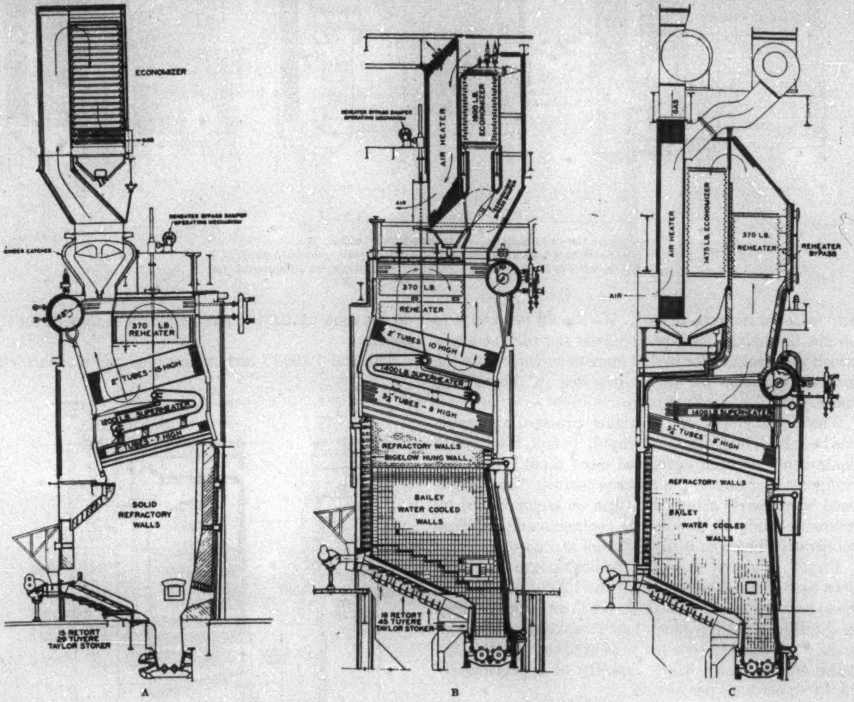

ECONOMIZER
CINDER CATCHER
REHEATER BYPASS DAMPER OPERATING MECHANISM
370 LB. REHEATER
2" TUBES - 15 HIGH
1200 LB. SUPERHEATER
2" TUBES - 7 HIGH
SOLID REFRACTORY WALLS
15 RETORT
29 TUYERE
TAYLOR STOKER
A
REHEATER BYPASS DAMPER OPERATING MECHANISM
AIR HEATER
1500 LB. ECONOMIZER
AIR
370 LB.
REHEATER
2" TUBES 10 HIGH
1400 LB. SUPERHEATER
3¼" TUBES - 8 HIGH
REFRACTORY WALLS
BIGELOW HUNG WALL
BAILEY WATER COOLED WALLS
18 RETORT
45 TUYERE
TAYLOR STOKER
B
GAS
AIR HEATER
1475 LB. ECONOMIZER
370 LB. REHEATER
REHEATER BYPASS
AIR
1400 LB. SUPERHEATER
3¼" TUBES 8" HIGH
REFRACTORY WALLS
BAILEY WATER COOLED WALLS
C

Fig. 8

*A*—Cross section of 15,732 sq ft 1,200-lb boiler—Edgar Station
*B*—Cross section of 15,093 sq ft 1,400-lb boiler—Edgar Station
*C*—Cross section of 6,971 sq ft 1,400-lb boiler—Edgar Station

Fig. 7 shows a cross section of the experimental series boiler tested at Purdue University and the Benson commercial series boiler in service in a European station.

The use of larger and larger turbo generator units in the past has, in general, resulted in a very satisfactory reduction in the unit cost of the units, their auxiliaries, and the building to house them. Probably larger units will be used in the future than are dreamed of today.

Manufacturers of turbo generators have patterns for turbine shells of various sizes. When they receive a request for a bid on a turbo generator unit of a specified capacity, they usually select the turbine shell for which they have a pattern that most nearly meets the specification and nozzle it for the specified capacity. This is, of course, more economical than to design a new shell for each bid.

Quite often the turbine shell selected is capable of being nozzled for considerably greater capacity, without

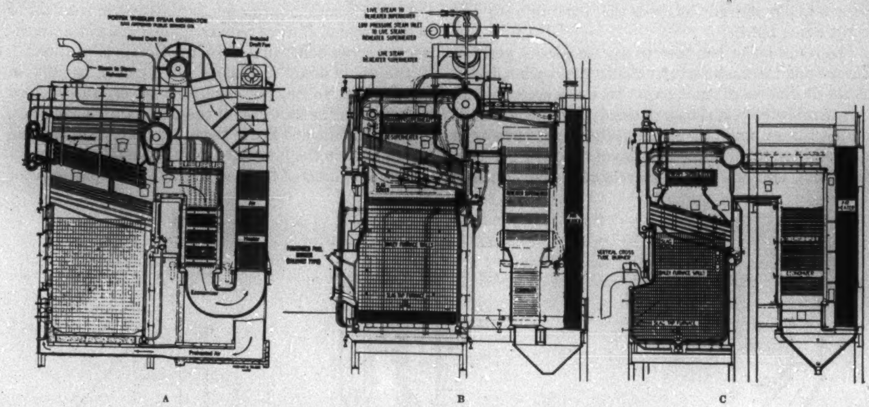


FIG. 9

*A*—Cross section of 1,525-lb boiler—Station B, San Antonio, Tex.
*B*—Cross section of 1,400-lb boiler—South Amboy Station, South Amboy, N. J.
*C*—Cross section of 1,400-lb boiler—State Line Generating Sta., Hammond, Ind.

any material increase in cost. We should be careful to obtain the maximum capacity from the turbine shells which we purchase, for in that manner we can obtain the greatest capacity per dollar invested in the turbine room.

The development of the higher pressure apparatus has been both interesting and rapid. In fact, the 1,200 lb equipment has been developed more rapidly than the equipment for any of the lower pressures. The designs used have clearly shown what can be accomplished by intensive study by competent engineers and by close cooperation between manufacturers and users.

Figs. 8, 9, and 10 show the various designs that have been used in the development of the 1,200-1,400-lb cross drum boiler from the 143,000-lb per hour boiler installed in the Edgar Station which had a capacity of approximately 3,575 lb per hour per section to the latest design being offered which has a capacity of approximately 25,000 lb per hour per section.

It is not necessary to discuss in detail the changes in design that have been made. A study of the illustrations shows very clearly the development of the apparatus.

Fig. 11 shows the parallel development of the 1,300-1,400-lb multiple-drum bent-tube boiler from the first one installed in the Lakeside station in Milwaukee to the latest ones installed in the River Rouge Plant of the Ford Motor Company in Detroit. They also show that progress is being made although the changes in design have not been as radical as in the development of the cross drum type.

The developments that have been made in the design of the 1,200-lb turbines and boiler feed pumps have been correspondingly satisfactory although the illustrations do not show up the changes as clearly as they do for the boilers.

The first 1,200-lb turbine installed had a capacity of 3,150 kw and was a single valve, twenty-stage unit as shown by Fig. 12. A number of similar machines were built with capacities as great as 10,000 kw but they all

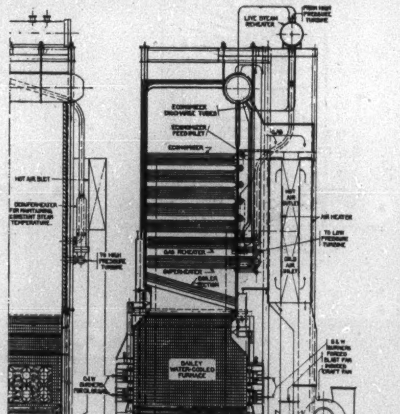

LIVE STEAM REHEATER
FROM HIGH PRESSURE TURBINE
ECONOMIZER DISCHARGE TUBES
ECONOMIZER FEED INLET
ECONOMIZER
HOT AIR INLET
DESUPERHEATER FOR MAINTAINING CONSTANT STEAM TEMPERATURE.
TO HIGH PRESSURE TURBINE
GAS REHEATER
SUPERHEATER
BOILER SECTION
HOT AIR OUTLET
AIR HEATER
TO LOW PRESSURE TURBINE
COLD AIR INLET
B & W BURNERS FORCED BLAST FAN INDUCED DRAFT FAN
B & W BURNERS FOR OIL BURN
BAILEY WATER-COOLED FURNACE
SECTIONAL FRONT ELEVATION
SECTIONAL SIDE ELEVATION

FIG. 10—CROSS SECTION OF PROPOSED 1,400-LB BOILER HAVING A CAPACITY OF 25,000 LB PER HOUR PER SECTION

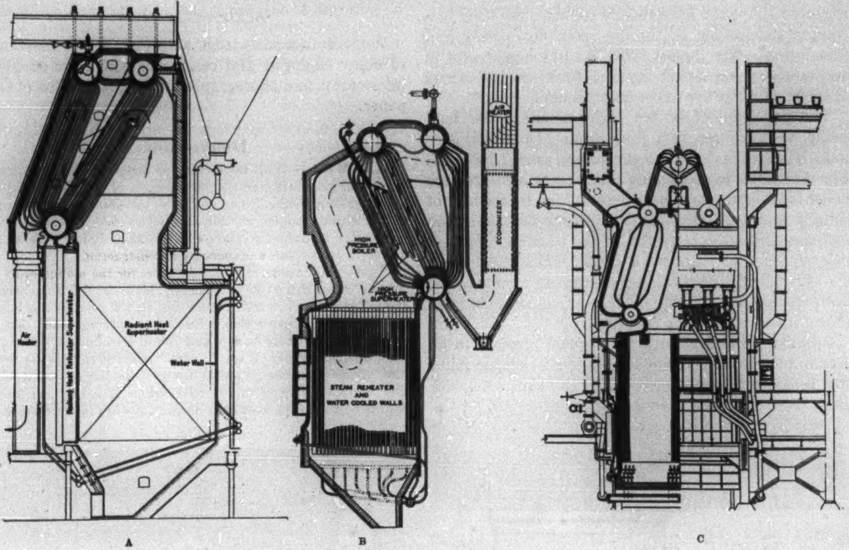

Air Heater
Radiant Heat Reheater Superheater
Radiant Heat Superheater
Water Wall
Air Heater
Economizer
High Pressure Boiler
High Pressure Superheater
Steam Reheater and Water Cooled Walls
A
B
C

Fig. 11

*A*—Cross section of 1,300-lb boiler—Lakeside Station, Milwaukee, Wis.
*B*—Cross section of 1,350-lb boiler—Northeast Station, Kansas City, Mo.
*C*—Cross section of 1,400-lb boiler—River Rouge Plant, Ford Motor Co., Detroit

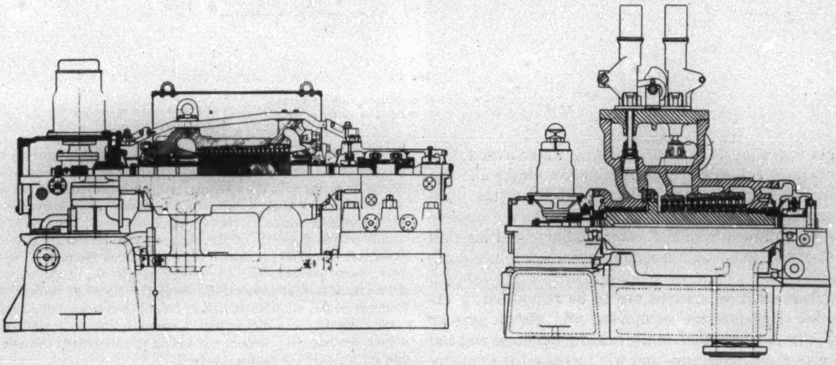


Fig. 12

*A*— 3,150-kw, 1,200-lb turbine—Edgar Station, Weymouth, Mass.
*B*—12,500-kw, 1,200-1,300-lb turbine—Edgar Station, Weymouth, Mass.

had the disadvantage that their economy at partial load was considerably less than at full load because of the single valve construction. To rectify this shortcoming, multiple valve turbines were designed giving very good economy from one-half to full load. A number of such turbines have been installed and are performing satisfactorily. Fig. 12 shows 1 five-valve design.

Another very interesting development has been the so-called vertical compound design shown by Fig. 13, in which the high-pressure turbine and its generator are mounted above the low-pressure element, resulting in a considerable saving in turbine room floor space and foundations. The largest 1,200-lb turbine generator in service today has a capacity of 110,000 kw but others of larger capacity are under construction.

The development of the high-pressure boiler feed pump has also been very rapid from the first 300 gpm unit to later ones having a capacity of over 2,000 gpm. The difficulties in developing satisfactory high-pressure boiler feed pumps have been accentuated by the lack of suitable variable speed 3,600 rpm a-c motors and by the fact that the water is heated by the extraction heaters to a temperature of about 440 deg F. These two factors and the difficulty of obtaining sound steel castings have been responsible for most of the difficulties that have shown up.

In making the decision on the steam pressure to be used in future construction we should also keep in mind that considerably greater capacity can be installed on a given piece of property if the station is designed for the higher pressures. If the circulating water available is limited, or the cost of constructing the intake and discharge is high because of local conditions, the high-pressure station has the advantage that greater capacity can be obtained from the water available and the unit cost of the intake and discharge tunnels will be considerably less.

Where existing stations are to be remodeled or extended, high-pressure equipment will permit greater capacity to be installed in the existing buildings and can be given load preference and will increase the economy of the whole station much more than the difference in economy between the high-pressure equipment and the existing equipment.

From a consideration of these facts, we can safely say the engineers of the future will meet the challenge of past accomplishments and will build steam-electric generating stations that will show considerably better fuel economy than our present stations and, furthermore, will cost considerably less per unit of capacity.

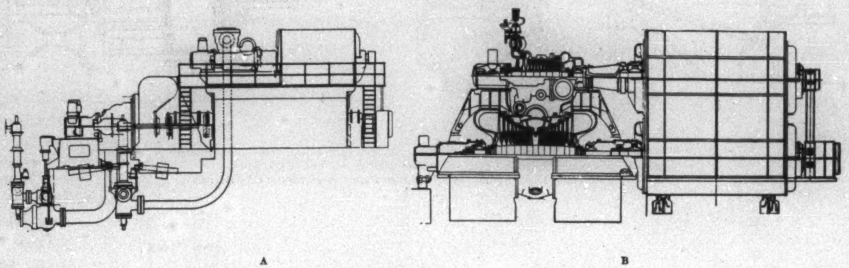


Fig. 13

*A*— 50,000-kw vertical compound turbo generator
*B*—110,000-kw vertical compound turbo generator

ACKNOWLEDGMENT

We wish to acknowledge with thanks, the assistance of many engineers and companies who have supplied information and photographs for the preparation of this paper.

## Discussion

**A. C. Weigel:** With the coming of higher pressures required for steam generating units, the question of the fabrication of higher-pressure boiler drums, and other high-pressure vessels connected with the boilers, has necessitated a thorough study, on the part of the manufacturers and the A.S.M.E. Boiler Code Committee, of proper, safe and economical construction.

Physical limitations and shop facilities for the manufacture of riveted boiler drums have normally been limited to material about 2⅝ in. thick, which means that on the average size boiler drums, riveted construction is limited to approximately 500 lb pressure for bent-tube boilers and 750 lb pressure for boilers of the cross-drum type. When the first boilers were built for pressures higher than these, it was necessary to use forged steel drums. The manufacturing of forged steel drums is a very expensive procedure due to the enormous amount of work in the forging of these drums, numerous heatings of the material during the process of the forging and the final finishing or machining of the drums, together with the wastage resulting from the large amount of material that must be discarded to insure the removal of all surface defects caused by the forging. As a result, the cost of the drums on the majority of the high-pressure boilers is, in many cases, more than 50 per cent of the total cost of the boiler. However, there has been one advantage in the use of forged steel drums, that is, that after careful study the A.S.M.E. Boiler Code Committee has allowed the use of forged steel drums of a higher carbon content and higher tensile strength than that allowed in regular fire box steel, therefore reducing to some extent the weight and thickness of the drums involved.

As fusion welding for tank work and pressure vessels has been in vogue for some time and as there has been quite a good deal of progress made in the studying of the procedure and the results obtained from these welds, the A.S.M.E. Boiler Code Committee several years ago, began a thorough study of the requirements necessary to assure uniformity of product and safety when using fusion welding in the manufacture of high-pressure vessels. After several years of study and discussion, the Code Committee, in June 1931, adopted rules for the manufacture of fusion-welded boiler drums. Besides describing to a great extent the method of procedure for manufacturing boiler drums, a principal requirement of the code that is leading to new uses of electricity in fabrication is that pertaining to the X ray test. This requires that all longitudinal and girth seams on fusion-welded boiler drums are to be X rayed or gamma-rayed to prove the soundness of the welds.

### ELECTRIC ARC USED FOR BOILER FABRICATION

A number of processes or procedures are followed by various manufacturers for fusion welding, but so far coated-rod, metallic-arc welding has been adopted almost universally. Plates are prepared with grooves of special shapes at their junction points with the proper slope along the edges of the groove to prevent undercutting and slag formation in the under-cutting. The weld metal must be deposited at a high temperature and puddled in place, using a coated rod of such type as to burn the oxygen in the vicinity while the metal is being deposited and also to coat the layer of hot metal with a protective coating to prevent absorption of oxygen and nitrogen by the hot material which, unless coated, has a high attraction for these gases. Each successive layer of welding must also have a tendency to anneal or stress relieve the underlying layer and great pains should be exercised in inspecting each layer to be sure that the laying in of that individual layer has not caused shrinkage cracks due to unequal expansion. These shrinkage cracks will not appear providing the structure is properly supported and the deposited material is sufficiently ductile. It is usually necessary to deposit, in the bottom of the groove, at least one layer of cooler material, this to act as a filler in the bottom of the groove. This material, being more porous, is cut out and refilled with higher grade material. Due to the fact that the last layer deposited is never of the same quality as the others, it is required to lay on beads so as to increase the thickness of the weld over that of the parent plate. This reinforcing bead need or need not be removed, although for practical purposes and for the correct reading of X ray films, it is advisable that it be removed, either by machining or grinding, as there are always ridges, small slag pockets and defects in this last reinforcing bead, and these may confuse the operator in reading the X ray films with the condition of the center portion of the weld.

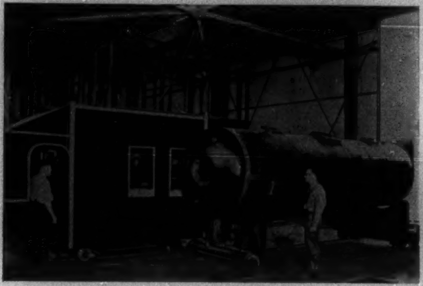


FIG. 1—FUSION WELDED BOILER DRUM BEFORE X RAY APPARATUS FOR TESTING QUALITY OF ELECTRIC WELDS IN $2\frac{1}{2}$ IN. BOILER PLATES

### X RAY USED FOR TESTING OF WELDS

The test plates attached to the ends of the drums for making the physical, chemical, and microscopic tests, if any, indicate the class of welding being laid in but do not give any assurance that the procedure has been uniform and that there is a lack of shrinkage cracks, slag pockets or gas pockets throughout the weld or along the border between the weld and the parent plate.

It has been proved that many processes of fusion welding with proper methods of control, make possible the production of deposited metal, equal or superior, in physical and chemical properties, to the boiler plate. On the other hand, it is undeniable that from its very nature fusion welding leads to greater variance in some respects than the steel plate manufacturing process. Therefore, the question is ever present in the minds of responsible manufacturers and users as to whether a welded seam is as good or better than the physical tested sample coupons. As a result it was necessary to adopt a satisfactory and positive method of non-destructive tests. This was commercially available in two ways: first, by the use of gamma rays, and second, by the use of X ray apparatus. As X ray apparatus was less costly and more readily handled, this has been the universally adopted method for the non-destructive test.

FIG. 2—X RAY PHOTOGRAPH SHOWING SLAG INCLUSIONS AND GAS POCKETS

FIG. 3—X RAY PHOTOGRAPH SHOWING POROSITY IN A BARE WIRE WELD

The A.S.M.E. Code as published at present specifies that for plates of a thickness of 3 in. or less, every portion of all longitudinal and circumferential welded joints of the structures shall be radiographed by sufficiently powerful X ray apparatus under a technique which will determine quantitatively the size of the defect with a thickness greater than 2 per cent of the thickness of the base plate; the X ray films to be submitted to an authorized inspector. Drums or shells of a wall thickness of over 3 in. need not be X rayed until such time as evidence is submitted to the Boiler Code Committee that X ray or similar means are developed that can be commercially applied to greater thickness. The manufacturer shall demonstrate his ability to produce sound welds in boiler drums or shells of a thickness not less than 2½ in., the joints of which are X rayed, in order to be permitted to construct boiler shells or drums with a shell thickness over 3 in. without X ray examination.

The limiting thickness of 3 in. was imposed at the time the code was adopted when commercial installations of X ray equipment were operating at a maximum tube voltage of 200 kv. Since then, however, several X ray installations have been placed in operation with tubes capable of withstanding an applied voltage of 300 kv, which permits X ray examinations of thicknesses of 4 to 4½ in., and without doubt the Boiler Code will shortly increase the requirements so that all plates up to 4½ in. must be subjected to X ray examination.

The Boiler Code also publishes reproductions of radiographs showing porosity and other defects which allow the determination of acceptable and non-acceptable welds. The code limits the serious defects in a welded joint by stating that a radiograph showing a defect, such as slag inclusions or a cavity, whose length exceeds 1/3 $T$ (where $T$ is thickness of joint) and where these defects are not separated from each other by at least 2 $T$, shall be non-acceptable. It further states that in case of such flaws being found they shall be removed and the joint rewelded and re-X rayed. The description of the technique employed must always be submitted with the radiograph to the inspector and this description must give the following information:

1. Thickness of the plate.
2. Distance of the film from the rear of the joint.
3. Distance of the film from the source of X rays.
4. The voltage impressed on the tube.
5. The current flowing through the tube.
6. The time of exposure.
7. The type of film used.
8. The type of intensifying screens.

A further requirement is that reference markers shall be placed along the seams to be X rayed. These markers must be accurately and permanently stamped on the outside surface of the drum or shell near the weld so that a defect appearing on the X ray film can be accurately located in the actual X rayed joints.

The code specifies that a monitor strip 2 per cent of the thickness of the plate to be inspected shall be used for each X ray film. In other words, if sufficient penetration is obtained to reveal the monitor strip which is placed on the boiler plate alongside the weld, the film complies with the code requirements. This monitor strip is used as a gage for determining the intensity of the defects. However, except where the reinforcement has been removed, it is apparent that a greater thickness has to be penetrated to reveal the defects in the weld proper than is necessary to reveal the monitor plate. In other words, on a 2-in. thick boiler plate the monitor strip will be 4/100th of an in. in thickness while the actual weld thickness would be approximately 2¼ in. including the reinforcement. Since the exposure time is a logarithmic function of the plate thickness to be penetrated, we see that with a given voltage and current applied to the X ray tube the weld proper will require an exposure twice as long as that required by the plate to obtain the same film or to detect defects in the same intensity. In other words, when the picture is taken in compliance with the present code, the exposure specified by the outside monitor piece is only about 50 per cent of that necessary to penetrate the weld proper adequately. For this reason it is very probable that a new type of gage will be adopted for determining the depths of defects.

Several studies have been made into the effect on the technique of welding, of the distances from the target to the weld and from the weld to the film. Since the image obtained on X ray films is a projection whose source is the focal spot of the target, the relations give a clear picture of the conditions involved. It is readily seen that since the focal point is not a combined source, sharper definition will be obtained with greater target to weld distance. Also the closer the film is to be to the object, the sharper will be the definition and the less the magnification of the defects shown on the film. However, since exposure time places a practical limit on the target to weld distance, a certain degree of sharpness must be sacrificed. The amount of distortion of defects with the target the same distance from the film increases the distortion of other defects on the target side of thick plates. Therefore, it is becoming necessary to make a table specifying the distance of a target from the plate on different thicknesses of material, and also to specify the distance from the front side of the plate to the film. The distance from the target to the film that seems from experience to be the most acceptable, is to vary 14 in. on plates from 1 in. up to 36 in. for plates 4 in. thick, and to require that a distance from the back of the weld to the film be held constant with a maximum of 1 in. This procedure will limit the maximum distortion of the edge of images from approximately 1.07 on 1 in. material to approximately 1.156 on 4 in. material.

With the above limitations as to the locations of material to be X rayed and the films, no trouble is encountered in the X raying of welded seams with respect to detecting cracks, incomplete fusion, elongated slag pits or other similar defects, such as elongated, closely-connected voids along the wall of a joint. Permissible and non-permissible defects of this type may easily be described quantitatively and the present limit of ⅓ of the thickness for these slag inclusions or cavities is satisfactory. So far it has been impossible to devise quantitatively the degree of porosity (defects in metal structure due to gas bubbles or slag inclusions) as shown on radiographs to limit satisfactorily the acceptable porosity in welds.

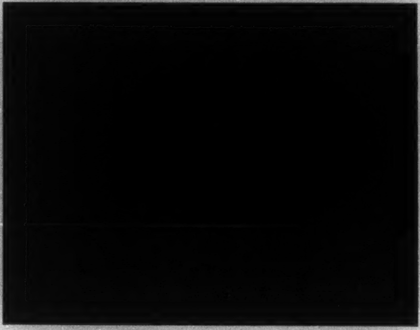


FIG. 4—X RAY PHOTOGRAPH SHOWING EXCELLENT WELD OF 2½ IN. PLATE

However, consideration is being given to this problem and there is no doubt that satisfactory standards will soon be adopted establishing more definite classification of allowable porosity and size and location of flaws, if they exist.

**D. S. Jacobus:** The authors of the paper should be congratulated on the successful outcome of their pioneer work in using high pressure steam for central power plant service. It required courage to install the first unit for 1,200 lb working pressure. There were many ideas in regard to the best form of boiler to use for the purpose. A drumless forced circulation boiler was considered, such as the so-called series boiler on which experiments extending over a number of years had been made by the writer's company. Various forms of natural circulation boilers were also considered. That the choice made was a good one has been shown by the results secured and the great number of high pressure boilers built along similar lines which are now in service.

It is easier to look back on accomplishments than to start at the beginning and overcome difficulties that may arise. There were many features to consider. At the time the first unit was ordered no means had been developed for determining the water level. Mr. Moultrop will remember the comments that this feature caused when it was discussed informally at one of the meetings of the Boiler Code Committee, as it seemed out of line to proceed before such an important question had been solved. Mr. Moultrop was convinced that high pressures would eventually be used and had the spirit of a true pioneer in proceeding with the development with the knowledge that certain features would have to be worked out and that there might be unforeseen difficulties.

A number of devices were suggested and tried for measuring the water level. After a painstaking investigation a water gauge glass was developed which met the conditions. The first boiler operated successfully from the start. There were certain minor troubles which were remedied but nothing of a fundamental character. In the boilers which followed there were further developments such as in the use of water-cooled furnace walls connected to the boiler circulation. The success of these boilers makes it seem that there is no particular reason from an operating standpoint why boilers of other types than those employing a natural circulation need be developed for the pressures and conditions under which they are used in central station practise.

The high head boiler shown in Fig. 10 was designed some time ago with an oil fired furnace for a high steaming capacity per section. In some later developments for pulverized coal firing it was found that a two-pass arrangement with the superheater and reheater in the first upward pass could be used to advantage.

It is stated in the paper that the series boiler may have possibilities that we do not realize at this time. The late Mr. Frederick Sargent was much interested in experiments which the writer's company made on this type of boiler, which began in 1916, and was convinced that there were possibilities of using a boiler of this type for power plant service, notwithstanding the care and skill required to operate it and certain untried and unsolved features. We coined the word "series boiler" to cover the arrangements that we tested, the first of which was a once-through forced circulation boiler with no steam and water drum, the second a forced circulation boiler with a reservoir into which the steam and water from the boiler passed before conducting the steam to the superheater section, and the third a forced circulation boiler used in connection with a natural circulation unit. Water was re-circulated through the boiler in most of the tests made on the second arrangement with the reservoir and in others the conditions were made such that no water accumulated in the reservoir in which case it served simply as a mixing chamber. The forced circulation boiler used in connection with the natural circulation unit was the forerunner of the so-called Calumet boiler and economizer arrangement, which has been largely used, and represented the type of installation that our experiments had shown to be the easiest to operate. Of the three arrangements first tested the once-through boiler with no steam and water drum was the hardest to operate. Tests of different forms of series boilers followed which finally led to the boiler installed at Purdue University, shown in Fig. 7 of the paper, and the automatic control supplied with this boiler which overcomes the operating difficulties experienced in the once-through series boilers first tested. With a boiler of this type all of the impurities in the feedwater pass from the boiler along with the steam, whereas in the Calumet arrangement and where the steam and water are conducted to a reservoir and some of the water is recirculated, clean steam may be secured with impure feedwater. This feature is referred to as it has assumed great importance in connection with central power plant service where we are called on to supply clean steam, and where in many cases washing the steam by water of a greater purity than contained in the boiler is resorted to. Features of this sort must be considered before installing a series boiler for central power plant service, in the same way that features that might give trouble had to be considered by Mr. Moultrop before installing his first high pressure boiler.

If the steam pressure approaches so closely to the critical that a natural circulation boiler cannot be used, a boiler of the series type would have to be employed. There are also certain special conditions involving the use of boilers of a minimum weight and height where a series boiler could be used to advantage.

Mention is made in the paper of regulating the temperature of superheated steam. This becomes more and more important as the temperature of the steam is increased. There are a number of ways in which this can be and has been done. At the South Amboy Station, of which a side view is shown at *A* in Fig. 9, the temperature of both the primary steam and the reheated steam is regulated and there is no reason why this should not be done in any case when so desired.

As stated in the paper, welded boiler drums are now developed that will probably become more generally used in the future and should result in lowering the unit cost of the steam generating units. All of the steam and water drums for boilers that have been built by the writer's company for working pressures of about 1,400 lb have been of seamless forged construction, nearly all being made of steel having a minimum tensile strength of 75,000 lb per sq in. in accordance with the specifications given in the A.S.M.E. Boiler Code. The rules for fusion welding in the A.S.M.E. Boiler Code do not cover the welding of steel of as high a tensile strength as this. The art of fusion welding is advancing rapidly and has been developed for safely welding steels of the higher tensile strengths; additional provisions will no doubt be included in the Boiler Code when the proper specifications and rules for safeguarding the constructions are available. A number are working actively on this problem, as well as on other features of fusion welding. It is believed by those best qualified to pass judgment that eventually fusion welding will be developed to a point where the highest quality will be used under the same rules as for solid plate, with no deduction for the strength of the weld, but each step must be based on scientific evidence and fact and the progress in formulating and adopting rules of the sort must necessarily be slow in order to insure safety.

**G. A. Orrok:** The authors of this paper have presented a history of high pressures and temperatures illustrated with examples of the most interesting of the American plants and we may note here the development of both the boiler and the turbine as applied to the high pressure plants in this country. It will be noticed that most of the development has been done with the usual design of straight tube and bent tube boilers, Fig. 10 alone being a departure and this only in a small measure from the standard types of construction.

In Europe, however, the attempts toward high pressures have led designers and constructors to the indirect as well as the series boiler. There are quite a number of the Schmidt indirect boilers in actual operation at pressures from 600 to 1,500 lb also the Loeffler boilers of which 7 or 8 boilers are in service at about 1,800 lb pressure with what is probably the highest commercial temperature of superheat, 932 deg. Besides these boilers we have the Sulzer single tube type which has just been introduced and the new boilers of the Atmos type with the revolving elements which are being experimented with in quite a number of places in Europe. Perhaps the most interesting developments of the European high pressure boilers is the velox boiler of the Brown Boveri Co. of which two units have been built and three more are under construction. The work of Escher Wyss and Company and Brown Boveri in the high pressure turbine field up to 2,800 lb pressure has been illustrated many times and these units are in daily operation. The question of centrifugal feed pumps seems to have been solved, one of the most satisfactory arrangements being that at Langerbrugge where the full steam pressure is used in the feed pump unit.

In general, it would appear that the costs of these high pressure stations do not exceed low pressure stations of about the same rank of economy or at the best, the differences do not exceed 5 to 10 dollars per kilowatt of prime cost.

In September 1930, before the British Association for the Advancement of Science in a paper on this same subject I showed some curves of the attainable use of heat per kilowatt hour sent out which are somewhat similar to those shown in Fig. 3 and on this plot I spotted a few of the annual station records which have come to my knowledge in the last few years as showing how closely our modern stations come to what might be considered as the standard of efficiency. This illustration (Fig. 5 of this discussion) shows the attainable curves as well as the median line drawn through the station record points. The study of some of the points will show that in a number of cases the modern stations with good load factor have exceeded what I term my ideal case, while in much of the earlier work the influence of low load factor is much more marked.

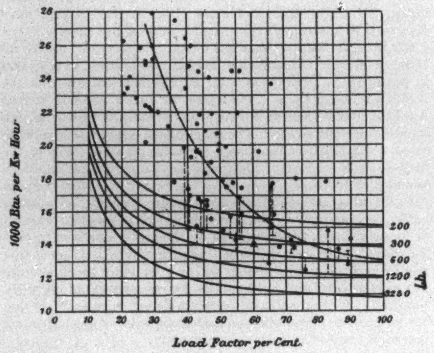


Fig. 5

We probably are still far from the point where we may pick out the ideal pressure and temperature which will give the best results over a wide field and I am personally inclined to believe that for a given load factor the optimum working pressure will probably not exceed 1,800 or 2,000 lb, while it is most probable that at smaller load factors lower pressures, 600 to 900 lb, without the use of reheat might lead to equally good commercial results. Meanwhile, the trend apparently is toward individual units with little cross connection and the best returns are always to be obtained in those stations in which the load factor is large and the loads are comparatively steady.

**F. A. Scheffler:** It does not seem possible that in 1884, when the writer first entered the boiler business, that practically all of the stationary boilers, principally horizontal tubular, portable, and vertical, were constructed in the most haphazard way and insured by reputable boiler insurance companies.

Rivet holes that did not coincide within an eighth of an inch—and sometimes more—were easily corrected by a drift pin, and the rivet driven home. This was *not* good boiler practise but it was permitted universally by the largest boiler manufacturers. One or two such firms did so much business, that, as they gave an insurance policy for one year free with each boiler, it was necessary to keep a resident inspector at the plant all of the time.

How was this inspection carried out and on what kind of a test was the policy given? On nothing more nor less than a hydrostatic cold water test—150 lb for 100 lb boiler pressure. If the boiler was tight at that test pressure, it was suitable and the boiler passed on and shipped to its destination, the certificate being sent by mail when countersigned by the home office of the insurance company. This does not intend to imply that the insurance company did not make strenuous endeavors to improve this horrible practise of riveting. After I had been at the plant about two months the vice president of the insurance company had a private conversation with me and described his past failures so that the manufacturers would realize that certain practises and methods of "laying" out sheets for punching should be changed and improved. He asked my cooperation, which I gladly gave him, but it required considerable time, diplomacy and some expense, to correct these troubles.

The very excellent work of the A.S.M.E. Boiler Code Committee and acceptance of the code by the States generally, has eliminated the careless and indifferent practise heretofore carried on. We now have, as further improvement in boiler construction, welded drums, and accessories, and in addition, satisfactory X and other rays for determining how perfect the weld is.

Credit should be given to the manufacturers for the wonderful research work they have carried on for several years in developing the welding art with all that that implies, to the present state of perfection.

**A. A. Potter:** The following information concerning the series steam generator at Purdue University may prove of interest:

The steam generator illustrated in Fig. 7A was designed and built for Purdue University by the Babcock and Wilcox Company It consists of a cylindrical water-cooled furnace placed immediately beneath a counter-flow economizer or convection section. There is no steam drum and the water which enters this steam generator passes through a continuous coil and leaves it as superheated steam. Outlet pressures of 3,600 lb per sq in. have been carried on this unit. By varying the ratio of fuel to water at a given flow rate the unit will discharge anything from warm water to superheated steam at 830 deg F. The feed water is delivered to the top of the convection section, where it is divided into two parallel circuits of equal length and flows downward countercurrent to the direction of the gas flow. The water as it leaves the two parallel circuits at the bottom of the convection section is carried to the bottom of the furnace coils by a single downcomer or equalizer. A sensitive automatic control system was developed by the Bailey Meter Company for the Purdue University unit, which is based on the thyratron tube as the source of power for the elements which regulate the supply of fuel, air and water.

Oil is used as fuel for this experimental unit, which was designed to deliver about 6,000 lb of steam and to operate at pressures of 1,000 to 3,600 lb per sq in. at the outlet, although at the lower pressures the friction loss is excessive on account of the small tubes used.

Selector switches are provided on the control panel so that the steam generator may be operated on manual control, automatic control, or a combination. The unit has been controlled automatically at outlet pressures varying from 1,500 to 3,527 lb per sq in., at final temperatures up to 830 deg F, and under rapid load changes equal to the entire range of the feed pump motor. The effectiveness of the automatic-control system increases with the pressure since, at the higher pressures, the specific volume of the steam is affected less by changes in temperature than at lower pressures. Normally, about 40 minutes is taken to bring the cold boiler up to operating conditions and to put it on automatic control, although this can be done by one man in about 20 minutes.

In a paper which was presented before the American Society of Mechanical Engineers on December 1, 1931, reports were given concerning the characteristics of the Purdue University series steam generator when operating at a variety of capacities, pressures and final steam temperatures. The behavior of the unit on a swinging load under automatic control was also demonstrated. These preliminary tests indicated that the efficiency of this steam generator varied between 60 and 70 per cent with a water evaporating capacity of 2,000 to 4,280 lb per hour and an outlet pressure range of 2,507 to 3,527 lb per sq in. Higher boiler efficiencies cannot be expected from an experimental unit of this type and size having a short, single pass convection section and a very high stock temperature. In a commercial installation this type of steam generator undoubtedly would be equipped with air heaters.

Since the preliminary results were presented before the A.S.M.E. the following studies have been undertaken:

1. Tests have been carried on with variable amounts of excess air and constant fuel input to determine the effect of furnace conditions on heat transfer rates.

2. Effect of fineness of atomization on the performance and heat transfer notes have been studied.

3. The limitations and practicability of the automatic control system have been investigated.

4. A special type of condensing calorimeter has been developed and was calibrated at temperatures up to 900 deg F and at pressures up to 3,500 lb per sq in. In a paper presented before the A.S.M.E. in December 1932, results of the measurement of entropy by the use of this calorimeter were reported. These included pressures varying from 1,900 to 3,500 lb per sq in. and temperatures of 709 to 780 deg F.

5. The laws governing fluid friction of steam at pressures up to 3,500 lb per sq in. and temperatures up to 830 deg F are now being investigated. Inasmuch as the film coefficient of heat transmission at the inner surface of a boiler tube is a function of the surface friction, the determination of the head loss should also supply fundamental data of use in calculating the temperature gradient from the outside surface of the tube to the fluid within the tube, when subjected to high rates of heat transfer. The determination of the head loss and the fluid film coefficient of heat transmission are of major importance in the design of high pressure forced circulation boilers. Viscosity of steam at a variety of pressures is a part of this study.

The investigations completed and those now in progress indicate that the series steam boiler is practical for a variety of pressures if equipped with a sensitive automatic control system. It is hoped that the studies now under way on fluid friction will result in new information of value to designers of this type of steam generator.

Suggestions will be appreciated concerning studies which should be undertaken at high pressures and of direct value to industry.

**G. G. Post:** To decrease investment costs of power plant equipment and, if possible, to improve present high reliability and efficiency standards seems to be the major challenge to engineers. Efficiency gains from exceeding 1,200 lb pressure are slight, as the authors show, because of rapidly increasing feed-pumping costs and steadily decreasing energy gains. It seems that the industry will gain most by reducing first costs through standardizing on a top pressure and advancing only slowly into higher temperature fields where extremely expensive metals and equipment are necessitated. Since October 1926, 1,200 lb pressure has been used at Lakeside with creditable performance. Availability has been consistently high. During the past year the four high pressure boilers had a combined availability factor of 93.7 per cent and the four high pressure turbines had 96.9 per cent availability. Each boiler-turbine unit averaged 22 starts and stops per month. Maintenance costs have been no higher on the 1,200 lb equipment than on the 300 lb. In 1931, 65c. per boiler per hour of operation was spent on maintenance for the four high pressure boilers. The amount would be reduced to 18.1c. per boiler per hour if the charge for changing the design of radiant superheater elements from the square to the round section in the original boiler were eliminated. Low heat release furnaces with steam and water cooled walls are the major reasons for these low maintenance costs.

The authors speak of the control of steam temperatures leaving superheaters and reheaters as a problem yet to be solved. Combination convection and radiant superheater and reheater surfaces offer a solution which will automatically control steam temperatures and maintain them almost uniform for loads varying from full to quarter. There is no need of separate reheat boilers, unreliable desuperheaters, nor partially effective mechanical dampers with this arrangement. Reheat in the same single boiler-unit in which the steam is originally generated obviates the necessity for proportioning steam to reheaters. Simplicity of operation as well as safety are major merits of the design mentioned. Reheat, as practised at Milwaukee, introduces minimum complications into the cycle. Operating performance at Lakeside offers absolute proof that it is not necessary to go to the series boiler-unit to find the answer for superheat control at higher temperatures.

Investment studies have shown that 1,200-lb equipment at Lakeside actually costs but $5.64 per kilowatt more than 300-lb equipment of equal generating capacity. A comparison of operating statistics with those of a new and modern 300-lb plant running under identical load conditions shows an actual fuel saving of 15.2 per cent for 1,200 lb over 300 lb. With coal at $4.00 per ton, or 64,000 Btu for 1c., it can readily be seen through reference to the authors' Fig. 6 that 1,200-lb equipment has netted a handsome profit.

Six years of operating experience with 1,200-lb equipment confirms the authors' statement that there seems to be no justification for spare steam producing units in a station, and that stations built in the future can be expected to have firm boiler capacity closely matching the full load steam requirements of the turbine-generator units. The Port Washington station is being built on this basis. It will initially have an 80,000-kw turbo generator using 1,230 lb gage steam pressure and 825 deg F steam temperature at the throttle and 825 deg F at the reheat point, and the single boiler will have a capacity equal to the turbine capacity at 90 per cent power factor, or 85,000 kw. Extensions are planned on the same basis.

Exception is taken to the statement concerning the progress made in the development of the multiple-drum bent-tube boiler from the first one installed in the Lakeside station in Milwaukee to the latest ones installed in the River Rouge Plant of the Ford Motor Company in Detroit. That the Ford Company installation represents progress is questioned. The layout at the Ford Plant was dictated by limitations imposed by having to install the equipment in an existing building, and for such limitations only, the design adopted by the Ford Company may be economically justified. When there are no such limitations it has been found that the three-drum bent-tube design fired from one side only, having boiler and not steam reheating, and with heat reclaiming equipment direcly behind the boiler, induced draft fans at or near the ground line, and a stack on the ground, is by far the most attractive from both an investment and an operating standpoint. Faith in this arrangement again is demonstrated at Port Washington where a design very similar to the original Lakeside high pressure design was found best. The *W* design Ford boiler with its heavy attendant supporting steel and a duplication of certain operating personnel, is not an improvement over the single sided design. Steam reheat, rather than boiler reheat, is considered a step backward.

In a 1,200-lb cycle, it is not necessary to pump water at 440 deg as mentioned by the authors, for the high pressure boiler feed pumps can readily be placed in the cycle ahead of the extraction heaters. The pumps can then take water at about 200 deg F and force it through the heaters at the higher pressure. Besides the advantage of handling low temperature water at a fairly constant temperature level, this plan requires approximately

15 per cent less pumping energy because of the higher density of 200 deg water.

**G. L. Knight:** The writer heartily endorses what the authors say about our duty to design for the highest dollar efficiency. However, there is a side to this question of power house design which must not be lost sight of. If additional generating capacity is necessary at a definite time, it may be necessary to be more conservative in our engineering than if, on the other hand, there is available time for experimenting with and working out the problems in installation.

By the same token if pioneer equipment has to be installed considerably ahead of the time it can be made assuredly reliable, then the interest charges during such an interval must be placed as a debit against the new design. Furthermore, where a station has been developed along certain definite lines for a considerable period, and experience has taught designers and operators how to make conservative designs even more reliable, it may be and usually is the part of wisdom to complete the station with similar equipment. This has been the case with the Hudson Avenue Station in Brooklyn, where 320,000 kw of capacity has been added during the past year at the same pressure and temperature as previously installed. The results, we believe, have justified the judgment exercised since the station has operated for the year 1932 at the average heat rate of 13,990 with a best month of 13,320 Btu per kilowatt hour.

Two 160,000-kw, 400-lb units, one placed in commercial operation in January and the other in May, have turned out approximately 1,000,000,000 kwhr of the 1,600,000,000 kwhr generated at Hudson Avenue during the year, or 1.3 per cent of the total utility generation in the country for 1932.

If I were to be concerned with the design of a new station today for the Metropolitan area, I would seriously consider 200,000-kw units at 1,200-lb, and 1,000 deg temperature, and at this temperature the reheat cycle can be eliminated in the interests of simplification without material sacrifice in economy. Such a station would be made as simple as possible with one boiler per turbine and practically no cross connections or duplication of auxiliaries. As part of a system having installed generating capacity of two and one-half million kilowatts, I believe sufficient savings in capital additions could be made by such simplification as would offset extra charges due to occasional necessary outages of such complete units, even though they were the most efficient on the system for a considerable period after their installation.

**R. C. Powell:** Messrs. Engle and Moultrop have given very clearly and concisely the present status of high pressure and temperature steam plant design.

As one who has had experience in the design of both moderate (450 lb) and high (1,350 lb) pressure plants, the writer wishes to confirm the statements given in the paper relative to the costs as affected by pressure. It is true that the costs are influenced to a much greater extent by the general design than by pressure, and the writer believes that on the whole increasing pressure up to 1,350 lb has a favorable effect upon costs. It is difficult to compare precisely the costs of plants since no two plants are sufficiently similar in design. The cost per kilowatt for two 50,000 kw vertical compound units with three boilers operating at 1,250 lb throttle pressure, 750 deg F with 750 deg F reheat was appreciably less than that for either of two 450 lb, 700 deg F plants each consisting of one 37,500-kw unit and two boilers. The cost for the 450-lb plants did not exceed $70 per kw which confirms the statement of the authors that increased efficiency has been obtained along with lower investment cost. The larger size of units for the higher pressure and the installation of two instead of one unit had, of course, a favorable effect upon cost which further confirms the statement that design and other factors may have more influence than pressure.

The actual gain in fuel economy for the higher pressure and somewhat higher temperature is of the order of 15 per cent.

In any consideration of the best pressure and temperature, the fact should not be overlooked that 1,250 lb pressure and 825 deg F with 825 deg F reheat is an established success whereas any moderate pressure, say 450 lb with temperature sufficiently high to even approach the efficiency of the higher pressure is still in the experimental stage. The writer agrees fully with the statement that temperature control is absolutely essential to successful and safe operation with high temperatures.

It appears to the writer that the economics are all in favor of higher pressure. There is no reason to assume that if high temperature, say 1,000 to 1,200 deg F, is successful at 450 or 650 lb it will not be so for 1,250 lb with a considerable gain in efficiency. It is not a difficult or expensive matter to increase the steam temperature with existing boilers, but nothing remains except complete abandonment if higher pressure is to be obtained. Hence, existing 1,250-lb plants may be changed for higher temperatures when they arrive. This will have a very favorable effect upon obsolescence which in the writer's opinion may be one of the serious problems of the future. It is certainly a problem now to many industries which at one time appeared as secure as the power industry at present.

Another advantage of high pressure not brought out by the authors, is the improvement in operating flexibility. The two years experience at Station A in San Francisco has fully demonstrated the operating advantage of 1,250 lb as against 450 lb. A number of load dumping and fast pick-up tests have been made. A load of 65,000 kw which is the maximum continuous rating for each of the units has been dumped a number of times with no case of tripping on overspeed. The load on each unit has been increased from 10,000 kw to 50,000 kw in 34 seconds with no carry-over and with very little disturbance to primary superheat or reheat temperatures. The reheat temperature is automatically controlled. The drum water level is automatically carried about 2 in. lower at light load and this is just about the swell when the load is suddenly applied to the boiler.

Fears regarding reheat complication either in design or operation are not well founded.

In every respect the use of high pressure at Station A, which is operated not on base load but as auxiliary to a large water power and transmission system, has exceeded expectations and the writer agrees with the authors' conclusions that future plants will have better efficiencies at lower costs and in addition better operating characteristics.

**Wm. S. Monroe:** About 10 years ago after our first 600-lb pressure plants had been laid out and we first began to make studies for a practical installation at 1,200-lb pressure, the estimates of cost for equipment indicated such an increase over that for 600 lb as to make the economic value of the higher pressure very doubtful. But the advances of the art have changed this condition, especially the improvements in boiler design for the higher pressure, and the improvements in the technique of boiler construction have so reduced the costs of the higher pressure boilers that our studies for the 150,000-kw State Line Unit No. 2 indicated that the cost of the 1,200-lb installation for a unit of that size would be little, if any, more than for a 600-lb plant.

There are many factors that tend to make the higher pressure plant less expensive. It is really the temperature that is the governing feature today, rather than the pressure. The 1,200-lb design enables reheating to be done at a higher pressure and carried to a higher temperature. The improvement in heat rate is about 8 per cent at 1,200 lb over 600 lb with 825 deg F initial temperature in both cases when full advantage is taken to reheat to 825 deg F at the most efficient pressure, with, of course, extraction for feed heating.

1. So far as the turbine is concerned, the higher pressure unit in a large size will probably be cheaper.

2. In the boiler plant, while the actual cost of the high pressure parts is somewhat higher for 1,200 lb, owing to the decreased

heat rate per kwhr, the cost of the complete boiler unit, including auxiliary equipment, is not greatly affected.

3. As the specific volume of the steam at 1,200 lb is about half that at 600 lb at the same total temperature, the high pressure pipe sizes are reduced in the ratio of about 1 to 1.4 in diameter, and often one pipe can be used in place of two that would be required for large units at 600 lb. The result is that the cost of piping for a large 1,200-lb unit is not increased at all and may be even less.

4. The auxiliary power, generally speaking, is decreased in the ratio of the decreased heat rate with the exception of the boiler feed pump, but when a reciprocating pump is used, the increased efficiency over that of the centrifugal pump more than covers the extra fixed charges due to the cost.

Though the throttle pressure is practically doubled, the safety valve pressure is increased in the ratio of about 1.75 to 1, and the boiler feed pump pressure to about 1.6 to 1. However, the pump efficiency is increased in the ratio of about 1.3 to 1 and the amount of water pumped decreased by about 1 to 1.2, consequently the boiler feed pump power is increased by $\frac{1.6}{1.3 \times 1.2} = 1.025$, or about 3 per cent, therefore practically no increase in total auxiliary power is expected. As against this, of course, the reciprocating feed pump is more expensive than the centrifugal, but not prohibitively so.

**W. I. Slichter:** At a recent meeting of the newly formed Institute of Public Engineering a session was devoted to costs of distribution. The representatives of the public service commission brought out data to prove that the cost of distribution could be brought down to 3 to 4 cents per kwhr. The representatives of the operating companies gave data to show that the cost could legitimately be as high as 9 to 10 cents per kwhr. This gives a mean of about 7 cents per kwhr. Now it is well recognized that the costs of generation at the power house range from 0.3 cent to 1 cent with a mean of about 0.7 cent. This raises the question whether, if a given amount of capital is available for improvement, it should not be spent on the distribution system where each gain of 1 per cent in efficiency will save 10 times as much in the actual cost of energy delivered as would 1 per cent gain in efficiency in the power house. In other words, would not the companies be wise to allocate 10 times as much capital to the distribution system as to the generating system?

**Glenn B. Warren:** The challenge which Mr. Moultrop gives to engineers is indeed one which should be carefully considered and be taken up, but it seems to me that in this connection there still is a greater challenge which the success of this high pressure development and the success of the mercury vapor process have issued, not only to engineers, but to the electrical utilities and to industry in general. This challenge is the opportunity which the successful development of the high pressure process and the mercury vapor process presents of combining plants capable of supplying jointly the electrical demands of the utilities, and the heat and electrical demands of industries, with resultant greatly reduced fuel consumption.

Of course, it will never be possible to secure such coordination of power and heat demand as to obtain complete utilization of all the opportunities presented for such savings. The relation in magnitude and time between the heat and power loads of the industries and the power loads of the utilities will never permit of perfect coordination. Each individual case must be considered on its merits, and the new equipment required can generally be justified economically only when there is a demand for the extra capacity which it produces.

On the other hand, an associate of mine recently made an estimate which showed that if all the industrial back pressure and bleeder turbines manufactured in each of the years 1927 to 1929 inclusive had been built for 1,200 lb initial pressure instead of the 200 to 400 lb pressure which they were built for and arranged to supply the same heat, these turbines would have had an aggregate capacity over and above what they did have equivalent to about one-fifth of all the condensing turbines manufactured in the respective years. Such installations would have been able to produce power on a net additional fuel consumption chargeable to power of about 4,000 Btu per kilowatt hour. Similarly, an extension of this investigation indicated that if all of these turbines which were installed to supply heating steam had been of the mercury vapor process type and as before arranged to supply the same demand for heat, these installations would have had an aggregate capacity over and above what they did have equivalent to almost one-half of that of all the condensing turbines manufactured in the respective years. These also would have produced power at a net additional expenditure of heat chargeable to power of 4,000 Btu per kilowatt hour. As it was, this amount of capacity was installed during these years in condensing turbines having a heat consumption of more than three times this amount. In other words, industry is providing us with a heat sump into which we can discharge our waste heat profitably instead of discharging it into the rivers, but we are not now utilizing this sump.

The successful utilization of this opportunity requires a considerable degree of cooperation and coordination between the utilities and the industries, inasmuch as the utilization of high pressure or mercury vapor in connection with industrial heat almost always results in more power available than can be used by the industry itself. Interconnections between the utilities and the industries will have to be made, and carefully considered contracts worked out. There are a few pioneers in this direction now; a number of jointly operated plants have been built and some are in operation. It seems that this offers an opportunity for us as engineers to assist in taking steps that will have a greater effect upon the conservation of resources and reduction of costs than almost any other line of endeavor we can now pursue in the power plant field.

**P. L. Alger:** This paper stresses the importance of further improving the efficiency of large central stations. The possibilities yet open in this direction through the reduction of the power losses in the boilers, turbines, and generators may be brought out in an interesting light through consideration of Figs. 3 and 6. These two figures indicate that for an average fuel cost of 6 million Btu per dollar, a reduction of 13 per cent in the station heat rate justifies an increased investment of $11 per kilowatt of capacity.

The efficiencies of typical boilers, turbines, and alternators for 75,000-kilowatt single-cylinder turbine units at the present time are approximately 85 per cent, 82 per cent, and 98 per cent respectively. The corresponding first costs of the equipment may roughly be taken as approximately $20, $8, and $4 per kilowatt of capacity.

These figures indicate that, if all the losses in the boiler could be eliminated, making it 100 per cent efficient, it would be worth 165 per cent of its present cost. Similarly, if the turbine could be made to have 100 per cent efficiency, it would be worth nearly 290 per cent of its present cost, and the alternator would be worth 140 per cent of its present cost.

The conclusions to be drawn are that in all three items of equipment the increased value to be obtained from higher efficiency warrants intensive further study by designers, but that the greatest possibilities exist in the turbine. Especial weight should, therefore, be given to efficiency when the design and selection of a turbine are being considered.

**A. C. Flory:** We note in Fig. 2 that the Edison Illuminating Company of Boston has reduced its coal consumption from 5.2 lb per kwhr in 1892 to about 1.1 lb per kwhr in 1932, or a reduction of approximately 80 per cent. Alongside this figure the increase in steam pressures and temperatures is shown, being an increase from about 350 lb saturated steam to pressures of 1,300 lb and 750 deg F. Of course, all of this reduction in coal rate is not accounted for by the change in the steam cycle itself. Roughly, the higher thermal efficiency of the more recent cycles would account for approximately 50 per cent of the decrease in specific coal consumption. There is little mention made of the fact, that since 1892 much higher condenser vacuums are common and that turbine and boiler efficiencies have advanced considerably. It should also be borne in mind that with interconnected stations and with more thought being given to the matter of flatter load curves, some advantage has been gained from that angle.

**A. H. Markwart:** The conclusions of the authors agree with the experiences of the Pacific Gas and Electric Company. The decision of this company to install high pressure units at Station A was made after a careful study had shown that such units would cost no more than for moderate pressures and there would be a marked gain in efficiency. It was not believed that maintenance and operating costs would be any higher and to date this has been true. Thirty years' experience with high head water power plants operating at pressures up to 1,000 lb has been excellent and indicated that some of the advantages of high head water power as against low head might hold for high pressure steam. This also has been confirmed by experience.

It has been feared by some operating men that a high pressure plant which operates entirely to supplement a hydro supply would be too complicated and inflexible for such service. However, experience has shown just the reverse to be true, and that a high pressure plant has marked advantages for such service.

**S. L. Pearce:** Curves are given in the paper to show the reduction in heat rate with increase in initial steam temperature and pressure, respectively, these being based on the reheat cycle. In my Presidential Address to the Junior Institution of Engineers I gave curves of a somewhat similar nature in Fig. 1, which showed variation in adiabatic heat drop with variation in steam pressure and temperature, and these curves tended to point out conclusively that increase in steam temperature gave a steady and almost constant increase in adiabatic heat drop, whereas increase in pressure did not show the same steady increase, which pointed to the fact that increase in temperature was a more important factor than increase in pressure.

The curves given in the paper do not appear to point out this factor so conclusively. For example, taking a constant pressure of 600 lb per sq in. the reduction in heat rate given by increasing the initial steam temperature from 750 deg F to 1,000 deg F is about 8½ per cent, whereas the increase in adiabatic heat drop given in my address for a similar variation is about 15 per cent. Again, assuming a constant steam temperature of 850 deg F, the reduction in heat drop by increasing the initial steam pressure from 600 lb per sq in. to 1,200 lb per sq in. is about 5½ per cent, whereas the increase in adiabatic heat drop given in my address for a similar variation is about 5 per cent.

It is appreciated that the two sets of figures cannot be strictly compared in that the problem is complicated very considerably according to the exact heat cycle adopted and the efficiency of the plant, yet one would have expected to have found a more general tendency to agreement than is demonstrated by Figs. 1, 2 and 3.

The curves for improvement in non-reheat cycle stations by increasing the steam conditions from 600 lb per sq in. 850 deg F to 1,200 lb per sq in. 1,000 deg F show a reduction in heat rate of about 9¾ per cent. The increase in adiabatic heat drop between these two conditions is, however, about 14 per cent.

As pointed out above, the foregoing figures are not strictly comparable, but the main point is that the figures in the paper do not seem to illustrate so clearly the advantage of temperature as compared with pressure in improving thermal efficiency.

I observe with interest the statement that: "Station designs in which one steam generating unit supplies all of the steam required by one turbo generator unit are becoming more and more generally accepted as the most economical," but I cannot trace having seen any convincing argument supported by comparative figures to prove this contention.

I do not agree with the statement that the availability of steam generating units and turbo generating units is about the same, as our experience would appear to show that the outage time for boiler plants is considerably greater than for turbine units. This is an argument against the suggestion of arranging the boiler plants individually for the turbine units.

Reference is made to the control of the superheat temperature, but it can be said that in England it has been found possible, by arranging the superheater so that it derives its heat partly by convection and partly by radiation, to obtain a very flat total temperature characteristic with variation in load. Variation in steam temperature with "dirtying up" of the boiler merely is a question of making suitable arrangements for cleaning the superheater surface and the surface of the boiler in front of the superheater satisfactorily during operation. Properly designed soot blowers operated carefully with reference to the temperature indicating equipment provided on the boiler plant make it possible to maintain a comparatively constant steam temperature.

**Charles H. Merz:** We are very much in agreement with the statements in the paper as regards the increased efficiency obtainable by higher superheat temperatures, and recognise that there are greater possibilities in this direction than by further increase in pressure. Our figures for the advantage obtained from higher pressures, however, seem to show rather lower savings, possibly due to greater allowances for the extra feed pump energy required and for the decrease in the average stage efficiency of the turbine as the pressure is increased.

There is a strong tendency in England, at the present time, not to go beyond 600 lb per sq in. and it is interesting to know that the authors consider that the use of higher pressures would not necessarily increase the capital cost of the station. This must, of course, be due to the fact that in America the design of high pressure installations has been fairly well established, whereas in this country we should be faced with considerable extra development charges at the outset.

We are just bringing into operation two new 600-lb pressure plants at Dunston on the northeast coast, and at Barking in the London area, the initial temperature in each case being 800 deg F. The former station has flue-gas reheat to the initial temperature. Judging from the contract prices it looks as if the adoption of reheat has had very little effect in increasing the capital cost when full allowance is made for the saving in steam consumption, and the consequent reduction in boiler and condensing plant.

The question of obtaining the maximum capacity from a given turbine shell is mentioned in the paper. It is interesting to note that by the adoption of reheat to the initial temperature the maximum capacity from the same turbine exhaust can be increased by something like 20 per cent without increasing the percentage leaving loss.

**A. McKinstry:** The desirability of utilizing higher steam pressures and temperatures together with interstage reheating and re-generative feed heating, has been appreciated by engineers for many years past and there has been a continued effort towards development in this direction. It is notable that the means adopted for attaining these ends has not been uniform throughout the world, the tendency in the United States being to utilize high pressures and moderate steam temperatures in the earlier schemes, while in Europe the line of development has been higher steam temperatures and moderate pressures. This is particularly instanced by the authors' statement that new stations are now being built in the United States using steam at temperatures from 825 to 850 deg F.

A power plant on a commercial scale using a steam temperature of 842 deg F with a pressure of 800 lb per sq in. was installed in Europe 7 years ago and there are as many as 23 stations in commercial operation at the present time with temperatures ranging between 825 to 842 deg F.

At the St. Denis Station of the Societe d'Electricite de Paris, boilers are just going into operation using a steam temperature of 878 deg F, while in London the first of the boilers at the Battersea Station of the London Power Company are ready for steaming, these boilers providing steam at a temperature of 875 deg F.

The authors have given figures for comparative economies made available by the use of increased steam pressures, and in the light of experience on this side of the Atlantic, 13½ per cent saving, when comparing a 1,200 lb per sq in. 850 deg reheat cycle station with a 400 lb 850 deg straight cycle station, appears to be rather optimistic, under normal working conditions, although apparently possible on theoretical grounds.

Mention is made of the progressive favor with which the one boiler per turbine arrangement is received in the United States. Possibly this position arose from the use of large base load stations in the United States where grid distribution of power has been developed to a very wide extent. In Europe, the one boiler per turbine arrangement is not now received with so much enthusiasm, and there is a distinct return to favor of the two boilers per turbine arrangement. The large amount of capital lying unproductive when large single boiler and turbine units are out of commission for any purpose is viewed with much disfavor by power engineers in Europe.

Reference is made in the paper to the development of the series boiler and illustrations of coil type boilers are given. So far in Europe the coil type boiler has not met with the success expected for it in some quarters, although series boilers of the type in which forced flow steaming economizers work with natural flow steam generating banks and large water-cooled furnaces have proved quite successful in service.

**I. V. Robinson:** Undoubtedly the higher pressures and higher temperatures do result in a reduced heat consumption per unit generated and also the capital cost of the plant is likely to be reduced as greater experience is gained with this type of apparatus. However, I question very strongly the advisability of attempting to balance so closely the charges due to extra capital expenditure against the savings due to improved efficiency. In the paper a 40 per cent load factor is assumed in order to balance these two items, but it is not known with any degree of accuracy what the load would be. When a new unit is set to work it usually gets the pick of the load and runs a very high load factor. It may thus take the load from an older unit which has not been installed very long and which is still very efficient. As a result this older unit may not get anything like 40 per cent load factor. In its turn the favored unit is superseded by another and so on. I doubt very much whether any unit in any generating station in the world will average a 40 per cent load factor over a period of 15 years. When there is this quite unknown factor of the use to be made of the machine is it really of any value to balance to a nicety the capital charges against running costs?

Then again, on the generating side of the problem we have certainly got into an area where the law of diminishing returns becomes effective. When a station with a heat consumption of less than 20,000 Btu per unit generated was a station of which the engineer could be proud there was plenty of room for improvement, but now when there are so many stations running down to 14,000 Btu the further possible advantage is really very small.

In considering the total price that the consumer has to pay for the units he gets in his radiator, etc., the generating costs are an insignificant amount and the reduction in cost due to 5 per cent or even 15 per cent improvement in thermal efficiency would be so slight that it is doubted if the purchaser would see any difference at all in his bills.

It seems that this constant striving after thermal efficiency is of greater interest to the engineers in charge, it becomes a matter of personal pride to get the lowest possible figures, but that it is a matter of negligible interest to the man on whom they all depend, *i.e.*, the consumer. If the brains which have up to now been used mainly, if not entirely, to reduce the generating costs, were able to do equally effective work as regards distribution then the purchaser would be interested, the cost of electricity would be reduced and the use would be increased enormously.

Although putting forward this view I appreciate the fact that it seems extremely difficult to find a point in the distribution system upon which a successful attack for the reduction in cost can be launched. We have gone through exactly the same phase of development in the power station. Up to a certain period the major efforts to reduce generation cost were confined to the turbine house, the boiler house being left as a somewhat dirty and undesirable area into which the engineers did not desire to intrude. Later the engineers extended their activities to the boiler house with the result that it has become a different place entirely and quite as efficient as the turbine house. Could not the same engineers now consider the distribution system? Possibly the solution may be the introduction of some simple form of transformer, perhaps a thermionic valve or some such device which could be installed on the purchaser's premises and would transform comparatively high tension current to the pressure required for domestic appliances.

**W. E. Wellmann:** German opinion is not against high pressure nor high temperature in any way. This can be proved by some stations in Germany using the one or the other. But the application depends largely on the especial conditions encountered.

It may be interesting to use high pressures up to 120 atmospheres in the case of an industrial plant with high consumption of process steam and high load factor, while on the other hand for a peak load generating station a pressure of only 30 atmospheres still is justified today.

One of the great difficulties that concerns the use of temperatures of 450 deg C and higher is the difficulty of obtaining suitable material; this difficulty still is so serious that the combination with high pressures does not seem very desirable at the present because it complicates the task of the designing and operating engineer. This has to be considered the more since ". . . the design and manufacture of high pressure generating equipment is in its infancy."

It is disadvantageous that the size of the turbine (kw) is chosen by the customer and the shell size by the manufacturer. I believe that in the near future standardization will be of help.

We agree with the conclusion in the paper that high pressure and high temperature have to be taken into consideration in every case of new installation of generating equipment.

**M. D. Engle and I. E. Moultrop:** The X ray has been an invaluable tool in the development of high pressure equipment from the very start and the discussions have shown the important part it is expected to play in future developments. No doubt the development and acceptance of welded pressure parts, inspected by means of the X ray will do much to accelerate the adoption of the higher pressures in the future and at the same time will aid in the manufacture of better and cheaper equipment for moderate pressures.

It is indeed encouraging to see such general acceptance of the results obtained in the earlier high pressure installations. We believe that a valuable lesson can be learned from this experience. Those responsible for the high pressure and high temperature installations have been very frank in discussing publicly their troubles and the means employed for overcoming the operating difficulties that have arisen. This frankness has engendered confidence in the reports and has resulted in a more rapid adoption of the higher pressures and temperatures than otherwise would have been possible.

Great credit is due the manufacturers of the equipment used for the capable manner in which they have executed their difficult tasks and for their willingness to have the troubles discussed so frankly in our technical meetings. We feel that they also have been benefited by this policy.

No doubt, in the future, we shall see many more full service installations where the electric utility will supply to the industries both electrical energy and steam for process. Such arrangements are so basically sound, where they are geographically possible, that we can expect rapid development along this line during the next business cycle. A frank public discussion of the problems arising and the solutions found will aid materially.

We were particularly pleased with the discussions submitted by our fellow engineers in Europe. It is very apparent that our ideas do not exactly coincide in the solution of the major problem of generating electrical energy at a lower cost. This makes their discussions doubly valuable. European engineers in general favor higher temperatures at moderate pressures while American engineers favor higher pressures at moderate temperatures. Actually, pressures and temperatures go hand in hand. The apparent lack of suitable materials of construction has held back the adoption of higher temperatures in the United States but European engineers have gone ahead and have outstripped us in this respect. Recent installations indicate however that American practise rapidly is catching up in the use of the higher temperatures. These installations are employing the higher pressures also.

The advisability of the one boiler per turbine idea has been questioned. The excellent papers by Hirshfeld and Moran on the reliability of large boiler units are the basis for the general acceptance of this fundamental in the United States. We believe that the idea is so sound that it will be accepted universally in the very near future.

In reply to those who have suggested that we should turn our efforts toward reducing the cost of transmission and distribution we would point out that this phase of the problem is receiving just as intensive study as the development of the generating stations. It is felt that the electrical engineers are waging just as courageous and just as successful a fight as the mechanical engineers. The American Institute of Electrical Engineers already has placed on record its accomplishments in transmission and distribution, and the battle still goes on unabated.

Electrical pressures have been raised from 115-230 volts to 220,000 volts. Cables have been developed so that today we are able to pull a 700,000-cir mil 14-kv three-conductor cable into the same duct formerly filled by a No. 4/0 14-kv cable. The quality has been improved with consequent reduction in failures, and due to lower losses, greater capacity can be delivered by a modern cable than by obsolete types of the same size and at the same voltage. Further advances have been made through the installation of low-voltage a-c networks, which probably will ultimately supersede the d-c systems, and the adoption of 4,000/2,300-volt a-c networks in suburban districts.

Electrical substations have been going through the same intensive developments. Better designs have resulted in speedier and more reliable breakers and more dependable protective devices. Large power transformers are now designed to give efficiencies as high as 99.60 per cent. These higher efficiencies and this greater reliability have been obtained at a lower cost, when all factors are considered. They are all doing their part in reducing the cost of the service, and this is being done in spite of the constant demand for better and more reliable service.

The battle for better service at lower cost is being waged on all fronts and is not being confined to any one sector.

# Recent Actions Taken By the Symbols, Units, and Nomenclature (S.U.N.) Committee

## Of the International Union of Pure and Applied Physics (I.P.U.) in Reference to C.G.S. Magnetic Units

BY ARTHUR E. KENNELLY*

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***Synopsis.**—In reference to the C.G.S. magnetic units, a brief historical outline is presented of the actions taken by international electrical congresses from 1893 to 1904, and by international technical and scientific unions from 1904 to 1932. Emphasis is laid on the results of the S.U.N. Committee meeting of July, 1932, as the latest development.*

*The present status of international agreement on C.G.S. magnetic units is unofficially presented, in the light of the historical background.*

*Turning to future possible developments, certain questions are pending for consideration, by either or both committees, in order to clear up any outstanding differences of international opinion over magnetic units in the classical C.G.S. system.*

*In order to convert the existing series of practical electromagnetic units (ohm, volt, ampere, coulomb, farad, joule, watt, henry and pramaxwell) into a complete system, international agreement must first be reached upon the two outstanding questions:*

*(a) Subrationalising ($4\pi NI$ or $NI$ for mmf).*

*(b) The unit of length to be adopted (meter or cm). Suggestions are offered along both these lines.*

### PURPOSE AND SCOPE

THE aim of this paper is to offer a brief unofficial account of what international actions have recently been taken in the matter of C.G.S. magnetic units, tending to eradicate some of the ambiguities that have pervaded magnetic literature during the last thirty years, and especially the actions in this direction taken during 1931-1932, by the International Electrotechnical[17] Commission (I.E.C.) and by the International Physical Union (I.P.U.), together with the present nomenclature status of these C.G.S. units, and what little yet remains to be done, in order to secure general international agreement. It will be seen that this is essentially a matter of names, definitions and nomenclature; since no changes have been suggested in the C.G.S. units themselves.

The second part of the paper relates to magnetic units in the practical, or *volt-ohm-ampere* series. Here relatively little has yet been accomplished. In order to extend this series into a complete comprehensive system, it appears to be necessary to secure agreement upon two very important questions: (1) Shall the mmf of a coil of $NI$ ampere-turns be $4\pi NI$ practical units, or $NI$ ampere-turns simply? (2) What unit of length shall be embodied in the system? Suggestions are advocated upon both questions.

### HISTORICAL OUTLINE SINCE 1927

In a paper entitled *Magnetic-Circuit Units,* read before the Midwinter Convention of the A.I.E.E., January 29th, 1930, the writer had the privilege of presenting a historical outline of magnetic units from 1861 up to that date. It will therefore not be necessary here to reconsider the history of the subject prior to 1927, when the International Electrotechnical Commission (I.E.C.) prominently entered the field.

The I.E.C. was projected in 1904, at the International Electrical Congress of St. Louis, and was inaugurated at London in 1906. It has been continuously in existence since that time. It has national committees in some twenty countries. Each such national committee is composed of representatives of its national government, local scientific and technical bodies, as well as various electrical industries. The general secretariat is in London; but the presidents, of which there have been eight up to this date, are elected successively from the various countries. Each national committee has its own president, secretary, and other officers.

The work of the I.E.C. is divided among nineteen separate advisory committees, each with its own president, and with a secretariat located in one country. Some advisory committees have delegates from a relatively small number of countries. Others have delegates from all or nearly all countries. Through the London central office, the different advisory committees convene at suitable times and places, to work out their own problems. As and when they arrive at agreements, they notify the central office, and report to the next plenary meeting of the I.E.C. as a whole. The plenary meetings are held about once in two years, and there have been nineteen in all thus far, distributed in time and place among twelve cities. The work of a plenary meeting consists largely of receiving reports from the various advisory committees, and of adopting them, as a body, by vote. The I.E.C. also receives and passes upon applications for the holding of international electrical congresses, in countries which desire to hold them.

The tasks undertaken by the various advisory committees relate broadly to electrical engineering, and

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[17] See bibliography for numbered references.

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especially to the standardisation of machinery, apparatus, specifications, methods and tests entering into electrical applications. In advisory committee No. 1 on "Nomenclature," definitions, symbols and units have been dealt with at various times.

At the plenary meeting of 1927, in Bellagio and Rome, a proposal was introduced by the Italian national committee, relating to magnetic units; both C.G.S. and practical. After some unsuccessful discussion, it was referred to a special subcommittee on "Magnetic Units" of the Advisory Committee on Nomenclature, for study and report, with a personnel group of representatives from seven countries. This subcommittee worked over the subject until 1929, without being able to reach an agreement, owing to the marked differences of opinion presented among the various national committees involved. The subcommittee reported in 1929, recommending that, in view of the large range of differences in opinion, the subject should be discussed in the national committees and placed upon the agenda for the next plenary meeting at Oslo in 1930. The subject was, in fact, ventilated in the technical press of several countries, in advance of the meeting of 1930.

The main difficulties in reaching agreement centered around the unit[3] name *gauss*, which had been adopted in 1900, at Paris. Magnetic literature all over the world, between 1900 and 1930, showed much confusion and ambiguity as to the meaning of this name. Some writers used it exclusively for the unit of flux density, or induction density $B$. Others used it exclusively for the unit of magnetising force, or magnetic intensity $H$; while yet others used it for both $B$ and $H$ indiscriminately. Moreover, some authoritative text books held that the quantities $B$ and $H$ were physically different, in which case, of course, the unit name *gauss* could only be applied to one; but to which was not certain. Other equally authoritative text books held, on the contrary, that the quantities $B$ and $H$ were physically identical; so that the *gauss* if applied to one, would also be applicable to the other. There was no middle ground between these two positions, and the first aim of the international subcommittee dealing with the subject, was to decide which of the two contentions should be supported.

When the magnetic units subcommittee met (June, 1930) in Scandinavia, its numbers were increased to include twelve countries, and its name was changed to Section B of the Nomenclature Committee, dealing with Electric and Magnetic Magnitudes and Units, (E.M.M.U.). After discussion, it was voted unanimously to adopt the convention, that for electrotechnical purposes, the quantities $B$ and $H$ should be regarded as being physically distinct; so that in a vacuum, or free space, $B = \mu_o H$, where $\mu_o$ is the *space permeability*, and is not a mere number, but a physical quantity having dimensions; furthermore that in the case of magnetic substances, $B = \mu H$, where $\mu$ is the *absolute permeability* of the medium, with the same dimensions as $\mu_o$; but the relative permeability of the medium would be $\mu / \mu_o$, a mere number.

These conventions having been adopted, the E.M.M.U. committee was able to deal speedily with other C.G.S. magnetic units which had offered difficulty. The following list of units and names was agreed to, either unanimously or by considerable majorities.[4]

(a) For the C.G.S. Magnetic Unit of magnetic flux $\Phi$, the name *maxwell*

(b) For the C.G.S. Magnetic Unit of flux density $B$, the name *gauss*

(c) For the C.G.S. Magnetic Unit of magnetising force $H$, the name *oersted*

(d) For the C.G.S. Magnetic Unit of mmf $\mathcal{F}$ the name *gilbert*.

The name *maxwell* had already been adopted in 1900 at Paris, for magnetic flux $\Phi$, as reaffirmed here under (a). The name *oersted* was applied to the unit of $H$, partly to indicate that, by convention, the name *gauss* being assigned to the unit of $B$, was not applicable to the unit of $H$. In America, the name *oersted* had been applied provisionally to the unit of reluctance $\mathcal{R}$, since 1900; but without international authorisation. The assignment of the name *oersted* to the unit of $H$ as in (c), leaves the C.G.S. magnetic unit of reluctance without a name, for the present.

The E.M.M.U. Committee also adopted the name *pramaxwell* for the unit of magnetic flux $\Phi$ in the practical series ($10^8$ *maxwells*) and the prefix *pra* as a general means of designating a practical unit derived from a C.G.S. unit.

The preceding resolutions, and others not directly within the scope of the C.G.S. units, were reported to the plenary convention of the I.E.C. at Oslo, and by it unanimously adopted, July 9th, 1930.

Following upon the publication of the I.E.C. actions on the C.G.S. magnetic units, comments appeared in the scientific and technical press of various countries. In general, these comments were favorable; but some adverse criticisms also appeared, mainly directed to two points:

(a) That names of savants should not have been given to C.G.S. units.

(b) That the name *gauss* should not have been given to the unit of $B$; but to that of $H$, in conformity with the usage of terrestrial magnetic observatories.

In regard to (a), the Paris Congress of 1900 had assigned the names *maxwell* and *gauss* to C.G.S. units, in view of the decision of the Congress of 1893, at Chicago, that working magnetic units should be kept within the C.G.S. system.

In regard to (b), it was pointed out that in view of the confusion in literature over the use of the name *gauss*, the I.E.C. convention necessarily brought embarrassment to some group of workers; but that the number who were in the habit of using the *gauss* for $B$ seemed to be much greater than those accustomed to using the *gauss* for $H$. Moreover, the earth's magnetic field is measured in air, which being a feebly magnetic medium, may be regarded as developing a flux density $B$ under the action of the magnetic intensity $H$ although, from a numerical standpoint, there would be no appreciable difference between the air values of $H$ and $B$. Terrestrial magnetic observatories are also accustomed to report their magnetic measures in terms of a special unit the *gamma* or $\gamma$, equal to $1/10^5$ *oersted*, and there had been no suggestion of disturbing this usage.

In view of any or all differences of opinion elicited by the publication of the I.E.C. Oslo resolutions, arrangements were made and announced early in 1931, to hold a special meeting of the E.M.M.U. committee at London, in September 1931, to review these C.G.S. recommendations.

## ESTABLISHMENT OF THE S.U.N. COMMITTEE BY THE INTERNATIONAL PHYSICAL UNION

The International Union of Pure and Applied Physics (I.P.U.), met at Brussels in July 1931, and established for the first time, an international committee on "Symbols, Units and Nomenclature," (S.U.N.). The S.U.N. committee elected as its Chairman Sir Richard Glazebrook, and as its Secretary, Dr. E. Griffiths. Since electro-technical units fall within the scope of the S.U.N. Committee, the I.E.C. extended an invitation to the I.P.U., to aid in the task of seeking international agreement on electric and magnetic units, through the coöperation of the S.U.N. and E.M.M.U. committees. This invitation was accepted, and the S.U.N. Committee was invited to have its members attend and take part in the London E.M.M.U. meeting, already scheduled for September 1931. The S.U.N. Chairman and Secretary were able to attend, and also the General Secretary of the I.P.U., Professor H. A. Abraham.

## ACTIONS OF THE LONDON MEETING OF E.M.M.U. COMMITTEE, SEPTEMBER 1931

At the opening of the E.M.M.U. meeting in London, September 18th, 1931, the President of the I.E.C., Dr. A. F. Enström, and the General Secretary, Mr. C. LeMaistre, took part.[17] The national committees of ten countries were represented:—Denmark, France, Germany, Great Britain, Holland, Italy, Norway, Poland, Sweden and U.S.A.

The agenda proposed by the American committee in February 1931, were then adopted as basis for procedure.

The first proposal on these agenda: (1a) was considered:

> "that the C.G.S. magnetic units and their accepted names, as fixed at the Oslo plenary meeting, should remain undisturbed"

This proposal was voted unanimously, two countries, however, abstaining, (Holland and Italy).

The next proposal (1b), related to a series of *practical* magnetic units, based on the *pramaxwell*, or *volt-second* as adopted at the Oslo meeting, with the *ampere-turn* as unit of mmf. After a long discussion, during which considerable difference of opinion was revealed, it was voted to defer action on these practical units until the national committees should have had further opportunity of examining the question.

On the particular question, however, of a practical unit of mmf $\mathfrak{F}$, and whether a coil of $N$ turns, carrying a steady current of $I$ amperes, should be taken as $\mathfrak{F} = 4\,\pi\,(NI)$ units, or merely $\mathfrak{F} = (NI)$, a vote was called for on the proposition that it should be $\mathfrak{F} = 4\,\pi\,(NI)$. Three countries were in favor of the proposition (France, Holland and Italy); while four voted against the proposition: (Germany, Great Britain, Sweden and U.S.A.). Two countries, Norway and Poland, abstained from voting. It is evident that there is much difference of opinion over this important question.

Item II of the agenda, on a conventional interpretation of reactive power in unspecified, alternating-current right-angle triangles, was next considered; *i.e.*, whether $+\,j$ *vars* should be taken as signifying inductively reactive power, or the reverse, when the basis of the diagram is not specified.

It was unanimously voted that a convention should be adopted; but that decision as to the direction, should be deferred until a new and definite American recommendation should be presented.

Some difference of opinion had been raised as to whether the particular direction recommended in the agenda ($+\,j\,P_r$ for inductively reactive power), was the more advantageous choice.

Item III of the agenda related to a proposed international adoption of the prefixed "*ab*" and "*stat*," applied to a practical unit, for the designation of a corresponding unit in the C.G.S. magnetic, or in the C.G.S. electric system, respectively. These prefixes have been and are in use, to some extent, in America; but have never been internationally adopted.

For lack of support to the proposal, no action was taken and the meeting adjourned.

## MEETING OF THE S.U.N. COMMITTEE IN PARIS

The S.U.N. Committee issued a questionnaire,[19] in December 1931, to physicists and physical societies in different countries, on "Electrical Units," calling attention to certain ambiguities in the definitions of fundamental electric and magnetic quantities entering into the C.G.S. system, and inviting opinions as to how these ambiguities might be eliminated, in order to arrive at international agreement. The replies to this questionnaire were collected. In view of the considerable number of physicists assembling in Paris during the week July 5th-12th, to attend the International Electrical Congress of 1932, the S.U.N. Committee called an informal meeting in Paris on July 9th, to discuss these questions, and especially the C.G.S. magnetic units.

The meeting was held under the chairmanship of Sir Richard Glazebrook, Dr. E. Griffiths of the British National Physical Laboratory (N.P.L.) being the Secretary. Nineteen persons, from eight countries, attended. The actions taken were informal, in the sense that the voting was not by countries; but by individuals.

The following propositions were adopted, either unanimously, or by considerable majorities:

1. Any system of units recommended must retain the eight internationally recognised practical units: *joule, watt, coulomb, ampere, ohm, volt, farad, henry.*
2. The C.G.S. system of units is suitable for the physicist.
3. A system of practical units including the above eight quantities, is derived from these by multiplying the C.G.S. unit by appropriate powers of 10.
4. That M. Abraham at the request of the conference, should prepare for consideration by the Commission, a preliminary report on the fundamental units.
5. The system of magnetic units may be based on the following two methods as alternatives:
   (a) The force between two elementary magnet poles, (Coulomb).
   (b) The force between two elements of current, (Ampère).
6. $B$ and $H$ are quantities of different nature.
7. The factor $4\pi/10$ should be retained in the definition of magnetomotive force.

The following table of electromagnetic quantities, which in accordance with suggestions received, has been revised since the meeting, is now proposed for adoption by the British representatives.

TABLE I—ELECTROMAGNETIC QUANTITIES

| Quantity designated | Symbol | C.G.S. units<br>Equation | <br>Name | Volt-ampere units<br>Unit | <br>Defining units |
|---|---|---|---|---|---|
| Flux | $\Phi$ | $\frac{d\Phi}{dt} = -E$ | Maxwell | $10^8$ maxwells | Volt-second |
| Induction or flux density | $B$ | $\int B \,.\, dS = \Phi$ | Gauss | $10^8$ gauss | Volt-sec/cm$^2$ |
| Mmf round a circuit | $F$ | $F = 4\pi NI$ | Gilbert or oersted-cm. | $\frac{1}{10}$ gilbert or<br>$\frac{1}{4\pi}$ ampere-turn | Amperes |
| Magnetizing force or field strength | $H$ | $\int B \,.\, \cos\epsilon \,.\, ds = F = 4\pi NI$ | Oersted | $\frac{1}{10}$ oersted or<br>$\frac{1}{4\pi}$ amp turn per cm | Amperes per cm |
| Permeability | $\mu$ | $\mu = \frac{B}{H}$ | Permeability | $\frac{10^9 \text{ gauss}}{\text{oersted}}$ | $\frac{\text{Volt-sec/cm}^2}{\frac{1}{4\pi}\text{ amp turn/cm}}$ |

## PRESENT STATUS OF THE C.G.S. MAGNETIC UNITS AS THE RESULT OF I.E.C. AND I.P.U. ACTIONS

It will be seen from the preceding S.U.N. recommendations and table, that there is agreement in all essentials between the findings of the I.E.C. and I.P.U. committees, so far as concerns the C.G.S. magnetic units. Both have recommended the convention that the quantities $B$ and $H$ should be taken as different, and that the unit names *maxwell, gauss, gilbert* and *oersted* for $\Phi$, $B$, $\mathcal{F}$ and $H$ are respectively satisfactory. If these conventions continue to receive support, the ambiguities and confusion which have pervaded international magnetic literature during the past thirty or forty years, should disappear. The only group whose current practise seems to be embarrassed by the conventions, is the terrestrial magnetic group, who have long been accustomed to employ the *gauss* for $H$. As has already been pointed out, however, these important scientific researches in terrestrial magnetism deal almost exclusively with magnetic phenomena in air, at ordinary temperatures and pressures. The numerical difference, between $B$ and $H$ in air under such conditions, is admitted to be only about one part in three millions; which is insignificant in the existing stage of measurement precision in terrestrial magnetism. There can be no present confusion in magnitudes, when the *gauss* in air is mentioned. Moreover the use of the *gamma* in terrestrial magnetic work is not interfered with.

In the United States, The I.E.C.-I.P.U. Conventions have been accepted by the National Bureau of Standards, the Society for Testing Materials, various committees of the A.I.E.E., and the U.S. National Committee of the I.E.C. Endorsements have appeared in electrotechnical journals. They are also used, to the exclusion of all others, in the "Report on Proposed American Standard Definitions of Electrical Terms,"[33] sponsored by the A.I.E.E., and recently published (August 1932). Up to the present date (November 1932), no objections seem to have appeared in North American literature to the I.E.C.-I.P.U.-C.G.S. conventions, and the only complaints raised have been that the previously existing C.G.S. unit name for reluctance has been removed, without designating any substitute. As a minor detail of symbology, however, an objection has been raised to the use by the I.E.C. of the symbol $\mu_o$ for space permeability. This symbol has been used to some extent in America for "initial permeability;" *i. e.*, the "normal permeability when both the magnetising force ($H$) and the induction ($B$) are vanishingly small." If it should be desired to retain the symbol $\mu_o$ for initial permeability, space permeability, or the permeability of vacuum, might be represented by some other symbol, such as $\mu_r$.

### MATTERS OUTSTANDING FOR CONSIDERATION IN RELATION TO C.G.S. UNITS

Up to this point in the paper, the writer has endeavored to present an unbiased historical picture of what the I.E.C. and I.P.U. have been able to do for clearing international understanding of magnetic unitology. In what follows, opinions and suggestions are submitted, in the role of an advocate rather than of a historian.

It is often supposed that the well known relation $B = \mu H$ *gausses*, which connects magnetic flux density with permeability and magnetising force, extends only to magnetic media, and has neither theoretical nor practical interest when free space, or non-magnetic media, are considered. Further examination shows, however, that this is too narrow a view to fit the facts. In a vacuum, free space, or non-magnetic media, the equation becomes $B_o = \mu_o H$ *gausses*; where $B_o$ is the space flux density, and $\mu_o$ the space permeability. In the C.G.S. magnetic system, the numerical value of $\mu_o$ is arbitrarily made equal to unity, and for purposes of mere computation, the equation might just as well be $B = H$, in which form it sometimes appears in text books and which would justify the view that $B$ and $H$ are physically identical. But in the C.G.S. electric system (commonly called the electrostatic system), the value of $\mu_o$ necessary to satisfy the equation is $\mu_o = 1/c^2$, where $c$ is the velocity of electromagnetic wave propagation, or nearly $3 \times 10^8$ meters per second. In any other system of electromagnetic units, a value of $\mu_o$ differing from unity must be used, even for purposes of computation, except in the Maxwell Q.E.S. (quadrant-eleventh gram-second) system. A few cases appear in the following table:

TABLE II

Values of $\mu_0$ Satisfying the Space Relation $B_0 = \mu_0 H$ for Various Systems

| No. | System of units | Value of $\mu_0$ |
|---|---|---|
| 1 | Classical or Maxwellian C.G.S. magnetic unrationalised | 1.0 |
| 2 | Classical or Maxwellian C.G.S. electric unrationalised | $1/(0.9) \times 10^{-21}$ |
| 3 | M.K.S. (meter-kilogram-second) unrationalised | $10^{-7}$ |
| 4 | M.K.S. (meter-kilogram-second) rationalised | $4\pi \times 10^{-7}$ |
| 5 | C.G-S.S. (cm-gram-seven-second) unrationalised | $10^{-9}$ |
| 6 | C.G-S.S. (cm-gram-seven-second) rationalised | $4\pi \times 10^{-9}$ |
| 7 | Maxwellian Q.E.S. (quadrant-eleventh-gm-second) unrationalised | 1.0 |

It has been pointed out in several countries that there are several classical C.G.S. magnetic formulas which should include $\mu_o$, in order to acquire general application. One of these is $B_o = \mu_o H$, often written $B = H$ for nonmagnetic media. This question of inserting $\mu_o$ in certain classical C.G.S. magnetic formulas where it generically belongs, ought to be considered by the E.M.M.U. Committee, independently of the I.E.C. Convention that $\mu_o$ has dimensions of some kind, other than a mere number. It has been claimed that $\mu_o$, as space permeability, is a fundamental physical constant. The Ausschuss für Einheiten und Formelgrössen has named it the "Induction Constant."

### QUESTIONS TO CONSIDER IN RELATION TO THE PRACTICAL UNITS

It will probably be generally admitted that the difficulties in the way of rectifying the C.G.S. magnetic units internationally are small compared with the difficulties of reaching agreement over the extension of the practical series of units into a complete comprehensive system. No changes have been made in the classical C.G.S. Magnetic system, which was adopted by the Paris Congress of 1881, endorsed, beyond any question of modification, by the Paris Congress of 1900, accepted by the Electrical Committee of the International Committee of Weights and Measures and was also endorsed by the S.U.N. Committee at the Paris meeting last July, under item (2) above referred to. On the other hand, the practical units are now nine in number: the *ohm*, *volt*, *ampere*, *coulomb*, *farad*, *watt*, *joule*, *henry* and *pramaxwell* or *volt-second*. These form a one-to-one series; but not a complete system. We may define a comprehensive practical system as any system of units susceptible of universal scientific measurements and computations, which includes the nine practical units as constituent elements. In order to complete the practical series into a practical system, certain additions must be agreed upon. These missing elements are of great importance. The first elements of the series are now more than fifty years old, and the completed system may last for centuries. Great care is therefore needed in choosing the best new elements; because while the choice is pending, we can carry on all our work in the C.G.S. system.

### QUESTION OF PRACTICAL UNIT OF MMF AND SUBRATIONALISATION

Probably the first question to consider is the definition of the practical unit of mmf. Shall it be the $1/4\pi$th part of an ampere-turn or just an ampere-turn? This is the old rationalisation question first raised by Heaviside in the seventies. He showed that rationalised C.G.S. units would be much simpler to think with, and work with, than those of the classical C.G.S. system; although the method by which he advocated rationalising, would have meant changing the magnitudes of nearly all the existing practical units and standards, and was quite unacceptable. Later on, it became known how to subrationalise a system; *i. e.*, to obtain the advantage of rationalisation through increasing the unit of space permeability $4\pi$ times, and diminishing the unit of space inductivity $4\pi$ times.

Karapetoff has recently presented a simple means of analysing any system of electromagnetic units, (setting aside the units of length and mass), in terms of five significant constants: namely, ($n$) the ratio of electric flux to the charge producing it; ($p$) the corresponding ratio of magnetic flux to the pole producing it; ($k$) the ratio of the mmf of a coil to the current-turns producing it; ($\epsilon_o$) the space inductivity and ($\mu_o$) the space permeability. He proceeds to show that a certain simple relation must hold among these five parameters in any workable system $\epsilon_o\,\mu_o\,c^2 = \dfrac{n}{k}\cdot\dfrac{p}{k}$. The three parameters $n$, $p$, and $k$ are indicated to be arbitrary numerics; while the product $\epsilon_o\,\mu_o$ has the same dimensions as the inverse square of $c$ the light velocity. On the basis of this analysis, we may define a system as subrationalised, when the ratios $n$ and $p$ are each equal to unity. If $k$ is also unity, so much the better. In both classical C.G.S. systems (magnetic and electric), as well as in the Q.E.S. system, the ratios $n$ and $p$ are each equal to $4\pi$. This makes unit pole produce $4\pi$ maxwells, and a corresponding numerical relation between electric charge and flux; whereas the basic idea should be that unit pole is a maxwell, and a unit charge is unit flux. So great is the advantage of this simplification that, as we all know, a large part of modern electromagnetic theory is carried on in the Heaviside-Lorentz rationalised C.G.S. system, and not in the classical C.G.S. system.

Various writers have indicated the simplification in working formulas brought about by subrationalisation. The books and papers thus far written in systematised practical units (Giorgi, Bennett, Karapetoff) have used $n = p = k = 1$.

The proposition to adopt $4\pi\ NI$ as the mmf of a coil in the practical system was raised in the E.M.M.U. London meeting of September 1931. At that time, the vote was 4 to 3 against the proposition, (two countries not voting). At the S.U.N. Paris meeting of July 1932, a similar proposition was carried by a vote of 10 to 3; so that the E.M.M.U. was in favor of rationalising, by a small majority; while the S.U.N. was opposed to rationalising, by a large majority. The question should be thoroughly examined in all countries and only finally settled, one way or the other, by a large majority. There is a danger that if the vote is not nearly unanimous, there may be a schism in the practical system, just as there has already been a schism in the C.G.S. system. We should thus face the danger of having a classical practical sect and a rationalised practical sect.

The arguments raised against practical rationalisation seem to be weak. One has been that certain well known relations now existing between the C.G.S. magnetic and C.G.S. electric systems would be lost if rationalisation were adopted. Granting that this is true, there can be no bad result in the case considered, because there will be a practical magnetic system; but no practical electric system. The duality of the present classical C.G.S. system will fortunately disappear from the proposed completed practical system. It has also been urged that the product $\epsilon_o\,\mu_o$ which is $1/c^2$ in the C.G.S. system, will have some other value in the practical system, when rationalised. This may be true in the general case; but is not true in either of the proposed completed practical systems. See Table III, Nos. 6 and 8.

Table III, prepared in accordance with the Karapetoff analysis, brings a number of different systems into comparison. Nos. 1 and 2 are the classical C.G.S. systems. No. 3 is the rationalised Heaviside-Lorentz system, No. 4 is the Maxwell practical system, as drawn up by its author and unrationalised. No. 5 indicates how that system would appear if rationalised. No. 6 is the Giorgi system, in the rationalised form presented by its author; while No. 7 is how it would appear unrationalised. No. 8 is the system for which there are a number of claimants, among them Dellinger, Bennett and Karapetoff. No. 9 is the same in unrationalised form, first suggested by the Committee on Units and Standards of the A.I.E.E. in 1891; although the implications as to the unit of mass ($10^7$ gm) were not then apprehended.

It has always been urged against rationalisation that if the factor $4\pi$ is taken out of mmf it will have to be inserted in permeance and reluctance in order to maintain the magnetic flux $\Phi$ unchanged in magnetic-circuit Ohm's law. The argument is that no advantage would be gained by the process. It must be remembered, however, that in the great majority of practical magnetic-circuits, magnetic material such as iron or steel

TABLE III

| No. | System | $L$<br>cm | $M$<br>gm | $T$<br>sec | $n$ | $p$ | $k$ | $\epsilon_0$ | $\mu_0$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Classical C.G.S. electric unrat | 1 | 1 | 1 | $4\pi$ | $4\pi$ | $4\pi$ | 1 | $1/c^2$ |
| 2 | Classical C.G.S. magnetic unrat | 1 | 1 | 1 | $4\pi$ | $4\pi$ | $4\pi$ | $1/c^2$ | 1 |
| 3 | Heaviside-Lorentz rat | 1 | 1 | 1 | 1 | 1 | $1/c$ | 1 | 1 |
| 4 | Maxwell practical Q.E.S. unrat | $10^9$ | $10^{-11}$ | 1 | $4\pi$ | $4\pi$ | $4\pi$ | $1/c^2$ | 1 |
| 5 | Maxwell practical Q.E.S. rat | $10^9$ | $10^{-11}$ | 1 | 1 | 1 | 1 | $1/4\pi c^2$ | $4\pi$ |
| 6 | Giorgi M.K.S. rat | $10^2$ | $10^3$ | 1 | 1 | 1 | 1 | $10^7/4\pi c^2$ | $4\pi/10^7$ |
| 7 | M.K.S. unrat | $10^2$ | $10^3$ | 1 | $4\pi$ | $4\pi$ | $4\pi$ | $10^7/c^2$ | $10^{-7}$ |
| 8 | Dell. Benn. Kar. C.G.S.S. rat | 1 | $10^7$ | 1 | 1 | 1 | 1 | $10^9/4\pi c^2$ | $4\pi/10^9$ |
| 9 | C.G.S.S. unrat | 1 | $10^7$ | 1 | $4\pi$ | $4\pi$ | $4\pi$ | $10^9/c^2$ | $10^{-9}$ |

has to be employed, and that the relative permeability of this material has to be included in the computation, usually through the use of a table or curve sheet. Since the relative permeability factor, has, therefore, ordinarily to be inserted, it is easy to include the $4\pi$ factor in the table or curve sheet, so as to have no necessity for introducing the $4\pi$ term separately. There is thus an economy of time and effort involved in the rationalised process of magnetic-circuit Ohm's law. The Ohm's law formula is, moreover, only one of many in which the $4\pi$ factor appears. In nearly all of them the rationalised formula is distinctly simpler than the unrationalised formula.

A real objection to rationalisation would be the divergence of the practical system from the unrationalised basic C.G.S. magnetic system. The main question to be decided would be whether the very real advantages of rationalisation are counter-balanced by the disadvantage of departure from the corresponding classical C.G.S. formulas.

### QUESTION OF THE UNIT OF LENGTH IN THE PRACTICAL SYSTEM

In addition to, but independent of the question of rationalisation, comes the question of the unit of length to be used. The choice of the length unit logically determines the units of area and volume. It has been shown by various writers, that in order to conform with energy and power requirements, (the *joule* and *watt*), there are only two units within the range of serious consideration; namely, the meter and the centimeter. Theoretically the *quadrant* is also included; but it is so large as to be out of discussion. The quadrant as a unit of length, exceeds the earth's radius. The square quadrant, as a unit of area, is about one-fifth of the surface of the globe, and the cubic quadrant, as a unit of volume, is of the same order as the earth's volume. No one has had the courage to propose these units seriously, and it does not appear that Clark Maxwell, who discovered the relation of the units in this system, regarded them as of a workable character.

The centimeter is a more convenient and familiar unit of length than the meter for most electrical engineering purposes. On the other hand, however, it is linked with a large and awkward unit of mass: $10^7$ grams, or ten metric tons. It is a question, therefore, whether in the general use of the practical system, for purposes other than electromagnetic, the disadvantage of this large mass unit might not outweigh the advantages of the centimeter.

It has been contended that neither the M.K.S. nor the C.G.S.S. system is permissible as a scientific unitary structure, for the reason that in neither of them is unit density the same as that of water. The unit density in the M.K.S. system is the kilogram per cubic meter, which is 1,000 times less than that of water. The unit density in the C.G.S.S. system is 10 tons per cubic centimeter, which is $10^7$ times the density of water. It is of course desirable to have the unit of density identical with that of water, from a practical point of view; but the failure to meet this condition probably is not so serious as some have claimed. For practical purposes, what we need is a table of specific gravities, or the densities of substances divided by the density of water. Once such a table has been prepared, the absolute density of water becomes of relatively small importance. It seems doubtful whether any practical system, otherwise acceptable, should be rejected because its unit of density is not that of any familiar substance.

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## Discussion

**George A. Campbell:** I should like to call attention to the practical results of the conventions set forth in this paper, as shown by a document which the paper says has used these conventions to the exclusion of all others. I refer to the "Report on Proposed American Standard Definitions of Electrical Terms"[1] sponsored by the A.I.E.E., with Doctor Kennelly as chairman of the committee in charge. It was published last August with a request for comments and suggestions.

Section 35 on "Units and Systems of Measurement" of the Group 05 on "General Terms" defines 5 c.g.s. systems with 27 of the c.g.s. units, next a practical system with 9 practical units, and finally an international system with 10 units. From these definitions the engineer can learn, for example, about the ohm, the abohm, the absolute ohm and the international ohm, but nowhere is he told what ohm is actually used in our shops. The engineer may be impressed with the multiplicity of c.g.s. systems but he cannot fail to find them confusing. Even if he is wise enough to skip the first four-fifths of the text and start in with the international system, he finds that every international unit definition refers him, in the end, to the corresponding absolute unit. This first leads him back to the definitions of the practical units, and then on back to the long, involved definitions of the c.g.s. units and c.g.s. systems.

Would it not be far better, in definitions intended for the electrical engineer, to define first, as briefly and directly as possible, the units which actually are used by the machine shop in the manufacture of electrical equipment, by the retail shop in the sale of electrical equipment, and in the shop talk at all A.I.E.E. conventions? The engineer could then get what he really needs without encountering the artificial difficulties which were invented when the leading scientists hardly had the grasp of electrical units which the youthful radio amateur now seems to have. It would, however, not be feasible to omit all reference to c.g.s. units because the electrical engineer will unfortunately encounter them in the literature of physics. This calls for the familiar conversion table to enable him, upon encountering any c.g.s. unit, to translate it into the shop unit which he really understands.

What I am suggesting is that in this A.I.E.E. glossary of terms relating to units both the order and the emphasis should be inverted. Put the shop ohm, the shop volt, the shop ampere-turn and the shop volt-second first and not the c.g.s. units. There would be no reference to c.g.s. units before the table at the end of the glossary. The shop units would be the basic units and the c.g.s. units would appear as derived units.

If you agree to this, it seems to follow that in his training the engineering student should start at once with the shop units. Then much later he would be introduced to the conversion table for use when, and only when, he encounters a c.g.s. unit in the literature. This plan should work perfectly with boys who have become familiar with the shop electric units as radio amateurs and household electricians. If this is the best procedure with students of engineering, it is, I believe, also the best procedure with high school and college students of physics. It seems quite certain that if a generation of engineers and physicists were trained in this way, they would continue to think and write in terms of shop units, and c.g.s. units would soon become of historical interest only. This, it seems to me, is a goal devoutly to be worked towards, and the present an opportune time for engineers to assist in accelerating the process of education.

Referring again to the A.I.E.E. electrical definitions: under the "International System of Electric and Magnetic Units," on page 34, occurs the statement, "The International Committee of Weights and Measures has decided to discard these units in the near future" in favor, it is implied, of the absolute practical units, as announced in the technical literature. This also calls for inversion, in my opinion.[2] Why? One among several reasons is this: the absolute practical units and all c.g.s. units lead to formulas which are infested with $4\pi$'s and the $4\pi$'s are an unmitigated nuisance in the shop, laboratory and study. The international ohm, ampere-turn, mechanical watt shop system is necessarily free from these $4\pi$'s and such a system is "much simpler to think with and work with," as Doctor Kennelly says. I wish there were time to take up Doctor Kennelly's paper point by point, but in the inverse order of presentation, and show how this inversion simplifies the subject and automatically eliminates one by one the difficulties which he sets forth. I refer especially to: ". . . the difficulties of reaching agreement over the extension of the practical series of units into a complete, comprehensive system," including the meter and ampere-turn, because it requires dropping the density unit and the $4\pi$ of the c.g.s. electromagnetic system; ". . . the ambiguities and confusion which have pervaded international magnetic literature during the last thirty or forty years." ". . . certain ambiguities in the definitions of fundamental electric and magnetic quantities."

To speed the adoption of the shop units as the normal, preferred, universal system, the legalizing acts for metric and electric units, in the United States and other countries, should be consolidated, revised and amplified. That the required changes are small is illustrated by the accompanying table.[3]

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[1] Report No. 2 of A.I.E.E. Standards.

[2] I cannot see, from the paper under discussion or from other reports of the deliberations of international committees, that the great advantages of relegating the c.g.s. systems to history in favor of a single, preferred system of units, based on the meter, kilogram, second and shop ohm, have adequately been considered by, or even clearly presented to, any of these committees. Many of their votes, therefore seem to me to lack finality.

A DEFINITIVE CHOICE OF MECHANICAL, ELECTRIC, AND MAGNETIC UNITS SUITABLE FOR A LEGALIZED SYSTEM

| Quantity | Unit name (bracketed names to be shortened) | Symbol and defining equation |
|---|---|---|
| 1 length | meter | $L$ |
| 2 area | [square meter] = square meter | $S = L_1L_2$ |
| 3 volume | stere = cubic meter | $V = LS$ |
| 4 time | second | $T$ |
| 5 power | watt | $P$ |
| 6 energy | joule | $W = PT$ |
| 7 force | [joule per meter] | $F = WL^{-1}$ |
| 8 pressure | [joule per meter per square meter] | $p = FS^{-1}$ |
| 9 mass | [kilogram] | $M = Fa^{-1}$ |
| 10 density | [kilogram] per stere | $d = MV^{-1}$ |
| 11 electricity | coulomb* | $Q$ |
| 12 electric current | ampere* | $I = QT^{-1}$ |
| 13 electric potential | volt* | $E = WQ^{-1}$ |
| 14 electric capacity | farad | $C = QE^{-1}$ |
| 15 electric resistance | ohm | $R = EI^{-1}$ |
| 16 electric conductance | mho | $G = IE^{-1}$ |
| 17 electric inductance | henry | $\mathfrak{L} = RT$ |
| 18 magnetomotive force | ampere-turn* | $\mathfrak{F} = NI$ |
| 19 magnetic flux | volt-second* | $\Phi = ET$ |
| 20 reluctance | [ampere-turn per volt-second] | $\mathfrak{R} = \mathfrak{F}\Phi^{-1}$ |

$a$ = acceleration in meters per second per second.

*The five starred units are to be about one-fiftieth of one per cent smaller than the corresponding international units.

The general adoption of these units should make it unnecessary to become familiar with more than one system of units. This would release human effort and soon eliminate the waste and confusion which are a necessary consequence of our present multiplicity of systems. Although the proposed single system of units merely is a selection and a re-alignment of present units, it is not a patchwork expedient. It would sweep away at one stroke all of the major difficulties set forth in Doctor Kennelly's paper.

Doctor Kennelly follows the international committees in considering that the classical c.g.s. magnetic system has been "endorsed, beyond any question of modification, by the Paris Congress of 1900." The literture of physics actually shows, however, that physicists do not consider the c.g.s. electromagnetic system of units suitable for all their needs. Theoretical physicists have substituted the Heaviside-Lorentz systems. Experimental physicists actually make great use of wattmeters, ammeters and voltmeters, together with the farad, ohm and henry. Fundamentally, the choice today is between c.g.s. authority and freedom to use the units which actual experience has shown to be "simpler to think with and work with than those of the classical c.g.s."

**C. L. Dawes:** Professor Kennelly's paper gives a very concise and yet comprehensive presentation of the developments and the present status of the I.E.C. and associated committees in the matter of the standardization of the c.g.s. magnetic units, both in their dimensional relations and in nomenclature. Likewise, the paper states that although practically unanimous agreement has been reached in the retention of eight of the practical units, yet names and even definitions have not as yet been assigned to the other practical units such for example as mmf.

Progress has been made in that definite names have been assigned to the c.g.s. magnetic units of flux, flux density, magnetizing force and magnetomotive force. Moreover, distinction between the controversial units of $B$ and $H$ decisively is indicated in their being assigned the respective names of gauss and oersted. Also the troublesome question of the dimensions of permeability $\mu$ appears to be settled by convention in a very rational manner.

However, so far the c.g.s. unit of reluctance is not named; it would seem highly desirable that a name be assigned to this unit, not only to complete the nomenclature of these related units, but also it is convenient to refer to a unit by name. The name itself is not material so long as it is in general harmony with electrical and magnetic nomenclature. It is the appropriate custom to name the units for savants and the name Weber appears to be the best adapted to this magnetic unit. In the very early days the name Weber was used as the name of the practical unit of quantity and later as the name of the practical unit of current; in more recent years it has been used unofficially in this country as the name of the practical unit of flux, but the names "voltsecond" and "pramaxwell," make the name Weber no longer necessary for the unit of flux. Hence the name Weber appears to be available and could be well recommended as the international unit of reluctance in the c.g.s. system.

It also would seem highly desirable that all the remaining magnetic and electrical units of the practical system be defined and named. This system is the most used by engineers and yet there has been little or no attempt to give names and definitions to the magnetic and electrostatic units (except henry and farad). In this respect I am in substantial agreement with Doctor Campbell.

I believe, however, that the factor $4\pi$ should be retained in the practical unit of mmf. This is in accord with proposition (7) adopted by the S.U.N. committee in Paris in 1932. Although a practical system should lean towards usefulness rather than toward a rational and fundamental derivation, it is questionable if the factor $4\pi$ does produce any more inconvenience when it appears in the numerator than it does when it appears in the denominator either in the physical dimensions of the magnetic circuit or in the permeability of vacuum. The author recommends the ampere-turn as the unit of mmf, stating that in engineering uses of magnetic materials their properties are given as data and curves in which the permeability factor is included, so that the $4\pi$ term in the denominator causes no inconvenience. This same condition has existed for a long time even under present conditions where the c.g.s. unit of mmf having $4\pi$ in the numerator is used. As is well known it has long been customary in scientific work of all kinds to plot the flux density as a function of the ampere-turn per unit length. Hence so far as such data or curves are concerned, it seems immaterial whether $4\pi$ appears in the numerator or in the denominator.

Furthermore all the present units of the practical system have a definite relation to the fundamental c.g.s. system, the unit of length being $10^9$ cm and the unit of mass $10^{-11}$ gram. Elimination of the $4\pi$ factor in the unit of mmf will break this rational relationship between these two systems, which I believe increases confusion and is thus highly undesirable.

With several years' experience, it appears to me that the so-called confusion which the $4\pi$ factor produces, even among students, is exaggerated greatly and is far out of proportion to the efforts being made to eliminate it. The physical picture of a unit charge or unit pole emitting $4\pi$ lines in a medium whose absolute permittivity or whose permeability is unity is simplicity in itself. In fact, to my mind this picture is a much more rational one than attempting to visualize a unit charge or a unit pole emitting only a single line and in a medium whose permeability is $4\pi$. Moreover, the unit charge and the accompanying $4\pi$ lines lend themselves very readily to the very fundamental work and potential relationships which are necessary in the derivations of electrostatic potentials and capacitances.

Only very recently I asked two of my classes one of which was composed of students who had only just begun seriously the study of magnetic and electrostatic units, whether or not the $4\pi$ lines emanating from unit poles or charges, was at all bothersome. They unanimously stated that this convention was very clear to them, in fact was much clearer than the unit line per pole or unit charge. In fact, it has long been our experience that students who are beginning electrostatic and electromagnetic studies have become greatly confused in attempting to use text books where the ampere-turn and the unit line per unit charge conventions are used.

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[3] This table is taken from the manuscript of a paper under preparation. The same units have been discussed in "Three Superfluous Systems of Electromagnetic Units" *Physics*, Vol. 3, No. 5, November 1932, pp. 230-239, and "A System of 'Definitive Units' Proposed for Universal Use" *Science*, Vol. 61, April 3, 1925, pp. 353-357.

Hence, it is in accord with my experience that the retention of the $4\pi$ term in the practical unit of mmf would simplify the understanding of magnetic relationships rather than confuse them.

I am heartily in sympathy with Doctor Campbell's "definitive" system and the simplicity which it implies, with the possible exception of the unit of mmf just discussed. However, I do not believe that the two fundamental c.g.s. systems should be discarded or even thrust too far into the background, since their units are derived in a simple manner from very fundamental postulates; moreover, even if the "definitive" or an equivalent system were legally adopted, I believe that these two fundamental systems still would be found to be very useful in certain types of scientific work.

**S. L. Gokhale:** The paper divides itself into two parts:

1. A summarized history of the subject up to the present date.
2. Recommendations by the author as to further changes.

The first part contains a table of symbols and units (Table I) suggested by the S.U.N. Committee, and recommended by them for adoption. Doctor Kennelly agrees with the opinions of this committee except on the question of rationalization; that is, Doctor Kennelly stands for omission of the factor $4\pi$ in the equation $\mathfrak{F} = 4\pi NI$, while the S.U.N. Committee has decided to retain it by a vote of 10 to 3.

Table I, column 3, contains what seems to be the defining equations of the concepts in column 1, although they are not specifically called by that name. Construing them as defining equations, we find that their sequence is the reverse of that of the scheme adopted by the I.E.C. and A.S.A. The I.E.C. and A.S.A. first define $m$ the magnetic pole strength. From this they derive $H$ and from $H$, $\mathfrak{F}$ and from $\mathfrak{F}$, $I$. The S.U.N. on the other hand first define $I$ and from this they derive $\mathfrak{F}$, and from $\mathfrak{F}$, $H$. Therefore, the agreement between the I.E.C. and the I.U.P. (International Union of Physics represented by the S.U.N.) as stated by Doctor Kennelly appears to apply to the names of the units and their magnitudes. I hope that it will be possible to work further with a view of arriving at an agreement as to the sequence of the definitions.

With reference to the omission of $4\pi$ in the equation $\mathfrak{F} = 4\pi I$, and its transfer to the equation $B_0 = 4\pi H$, it may be conceded that a large number of scientists favor the omission on the basis of the dimensional conception of permeability, but the point still is unproved.

The practical advantages of omitting $4\pi$ are more apparent than real. For instance, in machine design where the magnetic circuit is partly air and partly iron, the $4\pi$ cannot be eliminated from the computation, for if it is suppressed in the calculation of the iron part of the path, it will reappear in the air part. In only a few instances, such as design of transformers without leakage, can the $4\pi$ effectively be suppressed.

There are other cases in which, though the $4\pi$ does not enter into the numerical computations, has yet to be included in the new form of the equation, and it is possible that it may be forgotten, until the old practices are forgotten and new practices formed. For example, in transmission line calculation, engineers would have to use the formula

$$\frac{2\mu l}{4\pi} \log \frac{d}{r} \quad (\text{where } \mu = 4\pi)$$

in place of the present formula

$$2\mu l \log \frac{d}{r} \quad (\text{where } \mu = 1)$$

without the $4\pi$.

The best policy under the present situation, is a policy of compromise, which permits both parties to hold to their respective views, without interference from the other party. The decision of the I.E.C. in 1930 was the best possible compromise under the circumstances. It permitted one school of thought to assume the physical identity of $B$ and $H$ and to use the equation $B = H$ for space. This equation, though not obligatory to the opposite school, is permissible for them on the hypothesis that $\mu_0$ has been given arbitrarily the value of 1. The compromise also permitted followers of the dimensional conception of permeability to use separate names for the units of $B$ and $H$. Such a policy, though not obligatory to the non-dimensional scheme is quite permissible. This situation might have continued indefinitely without a conflict between the two schools until the question of dimensional character of permeability and the consequent difference in the physical nature of $B$ and $H$ could definitely be settled. An attempt to introduce $4\pi$ into the equation $B_0 = 4\pi H$ at this time would compel the followers of the non-dimensional school to abandon the idea of $B$ and $H$ being physically identical, together with the equation $B = H$. It seems to me that in proposing the change Doctor Kennelly is now going against the spirit of that compromise, which governed the decision of the I.E.C. in 1930. He admits, however, that the change should not be made on the basis of a narrow margin of votes as in the I.E.C. resolution of 1931, (R.M. 97).[4]

With reference to the substitution of the meter for the unit of length in the practical system, while there may be theoretical reasons for advocating this, I feel that in practise it only would add further confusion to the present condition by ending in giving us a third system in addition to the present two.

**Hans Lippelt:** During the discussion of the paper the use of "shop units" in preference to scientific units has been advocated. We do have shop units already, and I think this is a good opportunity to point out that some of them are bad. For illustration I wish to refer to the lb, which is often used in the shop as the unit of the mass. But it is utterly wrong to do so. The unit of the mass is lb-ft$^{-1}$ sec$^2$. If that term is too cumbersome for practical use, then let us find a short name for it and a symbol.

In going over the whole list of shop units, others also will be discovered which cannot bear scrutiny in the light of logic and accuracy. (For instance secondfeet, secft, is used for cubic feet per second.) I think that all such faulty units should be amended to become a true expression of their physical meaning. When short and new names for such units become necessary, exact definitions should accompany them.

Such a purging process should, indeed, be extended also to our technical script. It is customary to write $\sin^{-1}x$* to express an angle $\alpha$ whose sine is $x$, a method which is not compatible with the definition of a negative exponent as given in mathematics. Under this mathematical definition

$$\sin^{-1}x \text{ is equivalent to } \frac{1}{\text{sine } x}$$

and to nothing else.

If internationalism in the language of science and engineering is not objectionable, but striven for, then we might just as well accept the method as used in Europe.

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[4] Unconfirmed minutes of Meeting Section B on Elec. and Magnetic Units of Comm. No. 1, held in London, Sept. 18, 1931.

*The reader may answer that I have myself used this wrong method of writing. See A.I.E.E. TRANS., Feb. 1926, p. 408, col. 2, last line. My manuscript was correctly written. I had to change these mathematical terms to the customary form, to render my paper acceptable to the committee.

They write arcs in $x$ for an angle (arc), $\alpha$, whose sine is $x$.

$\left.\begin{array}{r} Ar\ \mathrm{Sin}\ y \\ \text{or } \mathbf{Ar\ Sin}\ y \end{array}\right\}$ for the hyperbolic angle (area), $V$ whose hyperbolic sine is $y$.

**W. I. Slichter:** In this paper there are two matters of very great interest to teachers of electrical engineering because they involve the setting up of two new conventions, different from previous practise and because it is the duty of the teacher to prepare the future generations of engineers to accept and use these conventions.

The first is the question of the algebraic sign and the vector representation of reactive power and explicitly: shall inductive reactive power be designated by $+j$ and drawn upward from the horizontal axis in vector diagrams? Either sign or direction may be justified mathematically and scientifically depending upon whether we take current or voltage as our reference vector.

The paper indicates that the international committee prefers a positive sign and upward direction for inductive reactive power, which means taking current as reference vector. This is probably quite satisfactory to those engaged in communication engineering. But those engaged in power engineering are dealing almost entirely with nominally constant potential circuits with one voltage common to all the circuits of the network and they therefore naturally think of voltage as the reference vector. In this case an inductive load means a lagging current and this is so common that we frequently hear the terms "lagging load" and "lagging power factor" where lagging means inductive. Thus these people would naturally prefer the negative sign and the downward vector for inductive power and the converse for anti-inductive or capacitative reactive power. The final choice primarily is one of suiting the habits of the majority of users or that which will involve overcoming the least amount of mental inertia.

The other question involves taking the constant $4\pi$ or $0.4\pi$ out of the magnetomotive force and putting it into the reluctance in the formula for the flux in a magnetic circuit. This again easily is justified scientifically if we ignore the very early development of the art, but more important, this change would put the law for the magnetic circuit in a form similar to that for the electric circuit and the dielectric circuit and make for uniformity and therefore for clarity, logic, and ease of teaching. Moreover, this is done already in most practical applications for every one of our magnetization curves of magnetic steels is plotted between flux density and ampere-turns and not gilberts or $0.4\pi$ ampere-turns. Here the mu and the $0.4\pi$ are made part of the reluctance or reluctivity of the material and the curves give us immediately the ampere-turns which is the quantity of practical interest, and not gilberts. If this change were adopted we would have the three outstanding relations in electrical engineering expressed in a similar manner:

$$\phi = \frac{NI}{R} \qquad R = \frac{1}{0.4\ \pi\mu A}$$

$$I = \frac{E}{R} \qquad R = \frac{\rho l}{A}$$

$$\psi = \frac{E}{R} \qquad R = \frac{1}{KA}$$

**A. C. Seletzky:** Whether or not $+j$ vars or $-j$ vars should be considered as representing inductively reactive power in unspecified alternating current right-angle triangles will probably be decided on the basis of whichever usage predominates in present practise. Both forms may be justified from the viewpoint of mathematical consistency. In view of the fact that $+jx$ has been internationally accepted for some years to represent inductive reactance, inductively reactive power in the form of $I^2(jx)$ would call for a positive sign, current being considered the axis of reference. On the other hand if the voltage were used as the reference axis, inductively reactive power in the form, $E^2(-jb)$, would require a negative sign.

In spite of the fact that capacity loads are encountered in practise, I have observed that engineers generally think subconsciously of reactive power as inductive when it is unspecified, by sheer weight of its more frequent occurrence. Since we generally label quantities, which occur more frequently on one side of an arbitrary line of demarcation as positive, the use of the plus sign to represent inductively reactive power would seem to be the more convenient form. An analogous situation is present in the consideration of positive angles as those which are drawn counter-clockwise from the positive axis of abscissas. Invariably when one is demonstrating anything involving an angle in space, one begins by drawing an angle in the first quadrant counterclockwise from the real axis: it is very probable that this usage grew from manual convenience in drawing angles in this manner and then led to the general acceptance of such angles as positive. It seems that a similar condition obtains in the case of reactive power and that inductively reactive power, from the standpoint of convenience alone, should be considered positive.

**A. E. Kennelly:** Doctor Campbell has well pointed out the advantages of a single system of units over the existing multitude of systems. He advocates extending the present series of nine international practical units (*ohm*, *volt*, *ampere*, etc.) into a complete comprehensive and so-called absolute system, embracing the *meter*, *kilogram* and *second*, with no separate electrostatic system, and with the *ampere-turn* as the official unit of mmf.; *i. e.*, with the system subrationalised. His "Definitive System," substantially the same as the Giorgi system, would be a great boon, if it could be used both in physics and in engineering, to the exclusion of all other systems. In detail, there is some question whether the *international ohm* should be taken at its existing value; or whether it should be first brought more nearly into agreement with the so-called *absolute ohm* of $10^9$ *abohms*; but this is a subsidiary question, outside of immediate discussion.

Professor Dawes points out that there is need for a name to be assigned to the c.g.s. magnetic unit of reluctance, now that the *oersted* has been taken for the unit of $H$. There are many who agree with him. It is to be hoped that a name for the c.g.s. magnetic unit of reluctance may be internationally agreed upon and adopted.

Professor Dawes supports Doctor Campbell's definitive system; except that he wants it left unrationalised, like the existing c.g.s. magnetic system. It was Heaviside and Lorentz who showed the marked advantages of rationalisation; so that a large part of electromagnetic theory is today written in the Heaviside-Lorentz c.g.s. system, instead of in the classical c.g.s. system, owing to the simplification thereby effected. There are thus two sects among basic electromagneticians; namely, the c.g.s. classicists and the c.g.s. rationalists. The question will have to be settled internationally, sooner or later, whether the applied electromagneticians, using practical magnetic units, are to be classicists or rationalists. It is not a question of what is right or wrong; but as to the relative balance of advantages. No classicist should be forced to use rationalised units against his will, and reciprocally. In view of the existing schism in the basic literature, and of the considerable difference of opinion that exists among engineers and technicians in regard to the practical units, it looks at present, as though we might have to recognize the existence of both classical and rational practical units; *i. e.*, both of the *ampere-turn* and of the *ampere-turn*/$4\pi$, and allow both these sub-systems to continue side by side, until international opinion shall have crystallized in favor of one of them; when the other can be formally discharged. This is virtually the state of affairs today in the basic c.g.s. world literature. Not only are opinions on this question of subrationalisation different among electrotechnicians in different countries; but there appear also to be differences of opinion in each of nearly all countries.

Mr. Gokhale points out that we still are unable to decide on scientific grounds, whether space permeability $\mu_o$ has or has not dimensions. We probably will all agree with him on this. There are good authorities on both sides of this vexed question. Ultimately, of course, there can be only one answer. Space permeability $\mu_o$ either is a mere number, or it is not a mere number. The question is of less importance to the engineer than to the physicist; but neither engineers nor physicists can use their symbols, units, or definitions logically, without coming to a conventional agreement upon the question. In the present state of our knowledge of electromagnetism, it probably is better to adopt an international convention, even if it should later be proved wrong, than to carry on indefinitely the confusion of the last thirty years. Thus far, we have had an agreement both in the I.E.C. and in the I.P.U. on the convention that $\mu_o$ has dimensions, and is not a mere numeric.

Mr. Gokhale also properly draws attention to the need of standardizing internationally the definitions of our magnetic quantities. It is very desirable to have this done. The definitions we still cling to are based upon the classical conceptions of magnetic poles, consisting of magnetic point sources. Most physicists admit the validity of these concepts and of the definitions resulting therefrom; but less artificial and more acceptable definitions might be arrived at on the basis of concepts of magnetic flux, obtained from the researches of Ampère, Faraday and Helmholtz.

Professor Slichter has drawn attention to the desirability of having an international convention as to the interpretation of right-angle power triangles when they do not specify the meaning of lagging power. Should lagging power, or $-j$ power, be taken to mean inductively reactive power, or the reverse? Here again is a need for a convention, and not a decision as to right or wrong. He favors lagging power going along with lagging current. General opinion among engineers seems to agree with him. Mr. Seletzky, however, seems to be of the opposite opinion. There probably is no large majority of opinion on this question; but it should be settled as a convention, for general convenience among engineers, and to avoid confusion.

# Empirical Equations for the Magnetization Curve

BY JAMES P. BARTON*

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***Synopsis.***—*An empirical equation is derived expressing the permeability in terms of the flux density over an approximate range of 100 to 6,000 gausses. The equation is of the form;* $\mu = P\beta^a$ *and is shown to apply to a variety of magnetic materials including certain alloys. Its greatest range appears to be for silicon content electrical sheet steels. A table is given listing the values of the coefficient and exponent for magnetic materials of various grades. Several curves and tables explain the salient features of the method. An extension of the method of derivation to other parts of the magnetization curve indicates their expression by similar laws or equations. Theoretical considerations lead to an hypothesis of four phases of magnetization coupled by three transitional phases for the entire magnetization curve.*

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## INTRODUCTION

THE design of magnetic circuits can be materially assisted by being able to express the relation between electric current and magnetism by means of equations. Numerous attempts have been made during the past century, and for the last 50 years the law formulated by Frolich[9] has been accepted as representing most closely the above mentioned relation. In the course of his study, Gokhale[1] has stated an equation that closely reproduces the measured data for that part of the $\beta$-$H$ curve above maximum permeability and including saturation.

But practically all of the work reported has been in the region between maximum permeability and saturation, leaving that part of the $\beta$-$H$ curve between maximum and initial permeability without a satisfactory expression. It is the purpose of this paper to present a simple equation derived experimentally, covering this part of the curve. As will be shown, the equation holds for commercial electrical sheet steels with silicon content, nickel-iron alloys, electrolyte iron and a cobalt-iron alloy. In the careful examination of the available literature on the subject, no reference has been found covering the procedure reported herein; consequently it is felt that the subject matter may be of value to those interested in magnetics.

*List of Symbols and Nomenclature*

$B$ = flux density, in gausses
$\beta$ = intrinsic flux density, in gausses ($B$-$H$)
$H$ = magnetizing force, in oersteds
$\mu$ = intrinsic permeability ($\beta/H$)
$1/\mu$ = reluctivity

## DERIVATION OF EQUATION AND GENERAL METHOD

In the course of study on simplified methods of design for magnetic circuits, it was observed that the ratio of permeability to the square of the flux density appeared frequently and was of considerable design value. In plotting this ratio *versus* the flux density $\beta$ on log-log paper, it was noticed that apparently a linear relation existed over quite a wide range of flux densities. If this was so, it gave a means for expressing the permeability in terms of the flux density over this straight part.

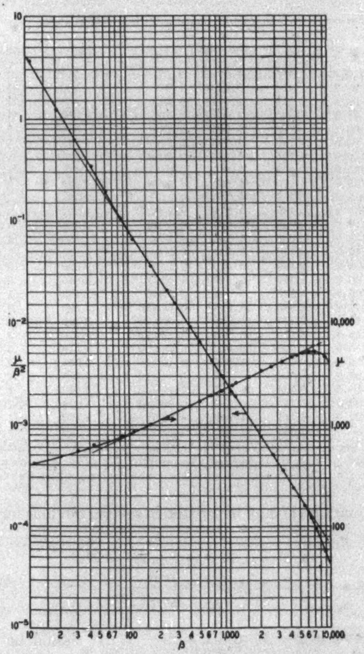

FIG. 1—PLOT OF $\mu/\beta^2$ *versus* $\beta$, AND $\mu$ *versus* $\beta$

For a 4 per cent silicon sheet steel, 29 gage, from data contained in Table I. $\mu/\beta^2 = 93.8\,\beta^{-1.53}$

The derivation is best shown by reference to Fig. 1. The equation for the straight portion is of the standard form $Y = PX^M$ where $P$ is the ordinate intercept of the straight portion extended and $M$ is the slope. From Fig.

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*Phelps Dodge Copper Products Corporation.

9. For references see end of paper.

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1, substituting the equivalent designations for $X$ and $Y$, gives the basic equation

$$\mu/\beta^2 = P\beta^{-M} \tag{1}$$

It will be observed that the flux density is the independent variable and the permeability, the dependent, with $P$ and $M$ being quantities whose values depend upon the nature of the material and are determined by graphical and analytical means from the curve. The values once determined for a given material allow direct calculation of the permeability as a function of the flux density, the equation holding over the straight part of the curve and for that material only. The data for the material are obtained from a sample selected to give the average characteristics.

TABLE I—DATA FOR SAMPLE NO. 2 AND CURVES OF FIG. 1

$\mu' = 93.8\,\beta^{0.47}$

| $\beta$ gausses | $\mu$ | $H$ oersteds | $\mu/\beta^2$ | $\mu'$ | Per cent deviation |
|---|---|---|---|---|---|
| 10.4 | 405 | 0.0257 | 3.75 | 279 | 31.1 |
| 20.2 | 496 | 0.0407 | 1.22 | 382 | 23.0 |
| 30.8 | 574 | 0.0538 | 0.605 | 464 | 19.2 |
| 44.5 | 645 | 0.0690 | 0.326 | 550 | 14.7 |
| 60.1 | 700 | 0.0859 | 0.194 | 634 | 9.4 |
| 84.3 | 781 | 0.108 | 0.110 | 742 | 5.0 |
| 116.0 | 875 | 0.133 | 0.0652 | 860 | 1.72 |
| 169.0 | 1,000 | 0.169 | 0.0351 | 942 | .58 |
| 238.0 | 1,170 | 0.204 | 0.0206 | 1,202 | − 2.74 |
| 293.0 | 1,294 | 0.226 | 0.0151 | 1,324 | − 2.32 |
| 403.0 | 1,489 | 0.271 | $9.2\cdot10^{-3}$ | 1,532 | − 2.89 |
| 516.0 | 1,703 | 0.303 | $6.4\cdot10^{-3}$ | 1,718 | − 0.88 |
| 678.0 | 1,938 | 0.350 | $4.2\cdot10^{-3}$ | 1,960 | − 1.14 |
| 849.0 | 2,170 | 0.391 | $3.0\cdot10^{-3}$ | 2,170 | 0.00 |
| 1,072.0 | 2,440 | 0.440 | $2.12\cdot10^{-3}$ | 2,420 | 0.82 |
| 1,160.0 | 2,590 | 0.448 | $1.93\cdot10^{-3}$ | 2,515 | 0.29 |
| 1,600.0 | 2,958 | 0.542 | $1.55\cdot10^{-3}$ | 2,910 | 1.62 |
| 2,044.0 | 3,280 | 0.624 | $0.785\cdot10^{-3}$ | 3,260 | 0.61 |
| 2,718.0 | 3,730 | 0.728 | $0.505\cdot10^{-3}$ | 3,735 | − 0.135 |
| 3,385.0 | 4,110 | 0.824 | $0.359\cdot10^{-3}$ | 4,120 | − 0.243 |
| 4,280.0 | 4,520 | 0.945 | $0.246\cdot10^{-3}$ | 4,610 | − 2.00 |
| 4,950.0 | 4,790 | 1.030 | $0.195\cdot10^{-3}$ | 4,920 | − 2.72 |
| 5,520.0 | 5,000 | 1.110 | $0.164\cdot10^{-3}$ | 5,220 | − 4.40 |
| 6,350.0 | 5,100 | 1.245 | $0.126\cdot10^{-3}$ | 5,545 | − 8.84 |
| 7,200.0 | 5,150 | 1.395 | $0.096\cdot10^{-3}$ | 5,900 | −14.6 |
| 9,000.0 | 4,715 | 1.910 | $0.0582\cdot10^{-3}$ | 6,490 | −37.7 |
| 10,730.0 | 3,655 | 2.94 | $0.0318\cdot10^{-3}$ | 7,120 | −95.0 |

The per cent deviation gives the difference between the calculated permeability $\mu'$ and the measured permeability $\mu$, by the expression 100 $(\mu - \mu')/\mu$. These data are for a medium grade 4 per cent silicon sheet steel.

Equation (**1**) may be written in several obvious forms, as

$$\mu/\beta^2 = 1/H\beta = 1/\mu H^2 = P\beta^{-M} \tag{1a}$$

$$\mu = P\beta^{a} \tag{1b}$$

$$H = \beta^{c}/P \tag{1c}$$

where: $a = 2 - M$ and $c = M - 1$. It should be observed that the slope of equation (**1a**) is negative while for (**1b**) and (**1c**) it is positive.

The data for Fig. 1 and Table I were obtained on a 4 per cent silicon sheet steel, 29 gage, using the tentative standard of the American Society for Testing Materials, low induction testing method A34-28, section C (1931 bridge method) on a frequency of 60 cycles, with several of the circuit elements changed to allow use of the bridge up to 12,000 gausses. The flux density range covered is from 10 to 10,700 gausses, with the apparent linear portion of the curve between 90 to 5,000 gausses. The equations for the latter flux range, using (**1a**), (**1b**) and (**1c**) with the slope $M$ equal to 1.53 and the intercept $P$ equal to 93.8, are

$$\mu/\beta^2 = 93.8\,\beta^{-1.53} \qquad \mu = 93.8\,\beta^{0.47} \qquad H = 0.01065\,\beta^{0.53}$$

With the equation established for the straight part, it is desirable to see how closely it reproduces the original data. In Table I, the $\beta$ and $\mu$ columns give the original data, with the rest calculated. The permeability $\mu'$ is that calculated by (**1b**). The deviation of the calculated from the measured curve is given by: 100 $(\mu - \mu')/\mu$, in per cent. At the flux densities of 100 and 5,200 gausses, the accuracy of reproduction is plus or minus 3 per cent, while between these limits the numerical value is considerably less, amounting to about the value of the accumulated errors.

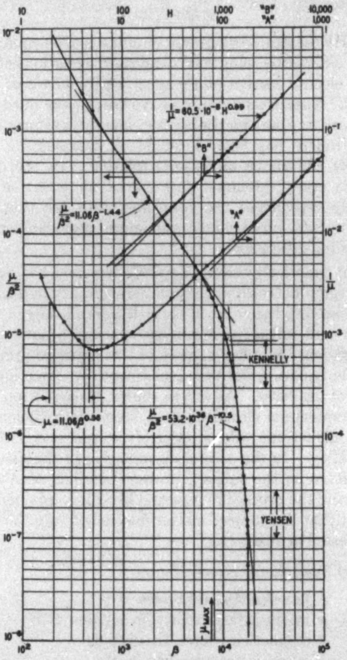

FIG. 2—PLOT OF $\mu/\beta^2$ *versus* $\beta$, AND $1/\mu$ *versus* $H$

For a poor grade of 4 per cent silicon sheet steel, from data contained in Gokhale's[1] paper (Table I and Fig. 1)

In Fig. 1, the $\beta - \mu$ curve is shown in relation to the $\beta - \mu/\beta^2$ curve. It will be observed that the apparent range of the straight part is much greater for the $\mu/\beta^2$ curve than for the $\mu$ curve. By analytical geometry the ratio of the ordinates and the ratio of the lengths of

TABLE II—COMPARISON OF MAGNETIC CHARACTERISTICS OF VARIOUS MATERIALS

| Sample No. | Name | Ave % si. | $P$ | $(2 - M)$ | $\mu''$ | Flux density $\beta$ Range covered | Flux density $\beta$ Equation range | $\mu_{max}$ at $\beta$ gausses | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | "A" | 3.75 | 194 | 0.360 | 590 | 10- 1,000 | 60-1,000 | | |
| 2 | "B" | 4.0 | 93.8 | 0.466 | 405 | 10-10,800 | 90-5,000 | 5,150 | 7,200 |
| 3 | "C" | 4.0 | 78.1 | 0.550 | 1,000 | 100-16,000 | 100-6,000 | 9,000 | 7,500 |
| 4 | Armco radio No. 5 | 4.1 | 329 | 0.290 | 760 | 10- 1,000 | 30-1,000 | | |
| 5 | Sheet steel | none | 28.6 | 0.545 | 833 | 500-20,200 | 500-6,000 | 3,440 | 8,600 |
| 6 | Electrical sheet steel | 4.0 | 11.06 | 0.557 | 366 | 400-17,600 | 750-6,000 | 1,400 | 8,000 |
| 7 | Follansbee Radio A | 4.1 | 155 | 0.44 | 950 | 20- 2,200 | 80-2,200 | | |
| 8 | Follansbee Radio B | 3.1 | 155 | 0.44 | 1,025 | 40- 2,400 | 100-2,400 | | |
| 9 | Follansbee Radio C | 2.0 | 151 | 0.41 | 650 | 20- 2,400 | 40-2,400 | | |
| 10 | "D" (48-51Ni-Fe) | | 971 | 0.445 | 3,050 | 4- 8,100 | 40-2,500 | 29,000 | 3,100 |
| 11 | 72-28 Ni-Fe | | 25.3 | 0.758 | 1,220 | 170-12,200 | 170-1,500 | 7,540 | 2,610 |
| 12 | Electrolytic iron | | 121 | 0.566 | 7,250 | 1,450-21,000 | 1,450-7,500 | 18,500 | 9,250 |
| 13 | 20-80 Co-Fe | | 21.8 | 0.555 | 585 | 350-23,200 | 350-3,800 | 2,580 | 7,750 |

Samples 1, 2 and 3 were measured in laboratory.

Sample 4 data from Armco curve No. 2040, from Bulletin "Armco Electric Sheets for Radio Applications."

Samples 7, 8 and 9 from Follansbee standard published sheets, R-1002-E, R-6002-E, and R-7002-E, respectively.

Samples 5, 6, 11, 12 and 13 from Tables IV, I, IX, VI and X, respectively, S. L. Gokhale's *Law of Magnetization*, TRANS. A.I.E.E.

The permeability $\mu''$ is that for the lowest value of flux density given in the column "range covered." The last two columns give the maximum value of permeability and the flux density at which it occurs.

the curves can be obtained from the slopes, for the same range of abscissa. For this sample, Fig. 1, and the same flux range, the $\mu/\beta^2$ ordinate is 3.29 times the $\mu$ ordinate. Likewise, the length of the $\mu/\beta^2$ curve is 1.66 times that for the $\mu$ curve. Being able to spread out the magnetization curve by use of $\mu/\beta^2$, tends to increase the accuracy in drawing the mean curve. Thus it may be said that the coefficient and the exponent for the equation are obtained by expansion of the curve; then by simplification of the equation a contraction of the curve results when plotted to the same abscissa scale. It should be observed that multiplying equation (**1**) by $\beta^2$ changes the slope from negative to positive, giving equation (**1b**).

Besides showing that this equation held over the flux range in question for measurements made in the laboratory, a considerable amount of published data was carefully examined, part of it being listed in Table II. Some of the data fell slightly short, either in the high or the low flux densities of fully covering the part of the magnetization curve being investigated. In all cases, however, the straight part existed. In most cases the deviation in reproduction was less than plus or minus 1 per cent over a wide range of flux densities. This equation appears to hold equally well for data taken by direct or alternating current methods.

Continuing with Table II, it will be noted that the coefficient $P$ covers quite a wide range of values, while the exponent $M$ does not vary so greatly. If it is considered that initial permeability exists at a flux density of one gauss, then the coefficient $P$ becomes the calculated permeability. See equation (**1b**). As the true $\beta - \mu$ curve approaches $\beta = 0$, it becomes tangent to the ordinate value corresponding to initial permeability, whereas the calculated curve is straight and intercepts this ordinate at an angle, when plotted on log-log paper. Thus the calculated permeability is less than the true permeability, for $\beta = 1$ gauss, and $P$ can undoubtedly be used to rate a sample of steel as to the relative magnitude of its initial permeability. Just how far this idea can be carried will have to be determined for a large number of samples.

The data in Table II for $P$ show an application of this idea, and can be seen for samples 1, 2 and 4 at ten gausses, and samples 7 and 9 for twenty gausses. Also, the two samples 5 and 6, which are poor grades of steel, have low values for $P$, the permeability being very low even at 500 gausses. Again, referring to samples 10 and 11 for nickel-iron alloys, 10 is particularly good with a permeability of 3,050 at 3 gausses, whereas sample 11 has a permeability of only 1,220 at 170 gausses. These values of $P$ for 10 and 11 are in keeping with the above mentioned idea and show how superior sample 10 is to 11 as a high initial permeability material. It is desirable to point out that the data on the various materials of Table II were selected from among many published and laboratory measurements to show that the method was general, holding for good and poor grades of silicon sheet steel and various alloys.

Just what function the exponent $M$ may infer as to the nature of the material, or a clue to its properties, is not clear at this time.

## EXTENSION OF METHOD TO OTHER PARTS OF THE MAGNETIZATION CURVE

It is of interest to compare the $\mu/\beta^2$ *versus* $\beta$ graph of a magnetization curve with that of the $1/\mu$ *versus* $H$ graph, which is an expression of Frolich's equation. See Fig. 2. The data selected are from Gokhale's paper[1] (Table I, Fig. 1). As the material is a very poor sample of sheet steel, the straight part is rather short and lies between 900 and 5,000 gausses, giving the equation: $\mu/\beta = 11.06\beta^{-1.44}$. The low valued coefficient indicates the very low initial permeability.

Continuing with Fig. 2, there appears a second straight part, between maximum permeability and saturation, which lies between that region investigated by Kennelly and that by Yensen. The equation for this sector involves very large numerical values for the coefficient and exponent, as is evidenced by the nearly vertical slope. The third straight sector is vertical and is that part for which ($\beta$) is constant, *i. e.*, saturation. These two sectors and the connecting part are ably covered by Gokhale's[1] equation (**30-2**): $\beta = S(1 - be^{-aH})$. The equation for the second sector involving the large valued coefficient and exponent, reproduces the curve very closely.

The only apparent straight part of the reluctivity curve, Fig. 2, is in the vicinity of and including saturation, and can be expressed by the equation: $1/\mu = 60.5$ $H^{0.99}\ 10^{-6}$. Comparing the accuracy of reproduction using this equation *versus* the reproduction data calculated by Gokhale's[1] (Table I-III), indicates that the former gives about half the accuracy of the latter, both operating over the same range. Noted on the reluctivity curve, Fig. 2, is that part reported in this paper, $\mu = 11.06\,\beta^{0.56}$.

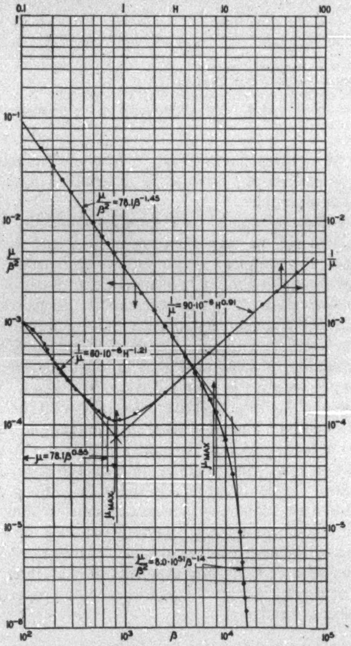

FIG. 3—PLOT OF $\mu/\beta^2$ *versus* $\beta$, AND $1/\mu$ *versus* $H$

For a good grade of 4 per cent silicon sheet steel, from data contained in Table III

The reluctivity curve has been shown by Gokhale[1] to be quite insensitive to variations in magnetic characteristics, and it only appears as a straight line when saturation is approached. Many text books, when showing the magnetization curves, use co-ordinate paper with scales so arranged as to crowd the low induction region, seemingly to indicate that the only region of interest is above maximum permeability to saturation, whereas all portions of the $\beta - H$ curve are equally important. It is this latter range that appears as a straight line when plotted to the same scale to illustrate Frolich's law and which is misleading in appearing to cover the entire $\beta - H$ curve. The use of log-log or semi-log paper for expressing the magnetic relations has been more private than public. It is urged that wherever expedient, the log-log and semi-log papers be used, especially in text books so that the magnetization curve may be revealed as completely as possible, without favoring any one section.

In Fig. 3 are shown curves for a 4 per cent silicon sheet steel of good quality, in the flux range of 100 to 16,000 gausses. The equations of $\mu/\beta^2$ *versus* $\beta$ for the two straight parts on either side of maximum permeability are given. For the reluctivity curve, it appears that the region above maximum permeability, for this material, can be expressed by an equation of the same form as discussed for Fig. 2, with the range considerably increased. It is interesting to note that the reluctivity curve is not as straight below maximum permeability as it is above. By drawing in the average straight line, it was found to intersect the extended straight line from the other straight part, at maximum permeability. This has been observed for several other samples and may be of some interest, or value. The degree of reproduction for the lower part of the reluctivity curve is very poor compared with that for the upper part using the equations noted on the curve in Fig. 3. Of greater interest is the fact that the permeability below maximum can be much more closely stated by $\mu = 78.1\,\beta^{0.55}$, as derived by the method of this paper, than by $\mu = 16{,}660\,H^{1.21}$, as derived from the reluctivity curve. This can be seen by referring to Table III which gives the deviation in per cent for the two equations.

## THEORETICAL CONSIDERATIONS

From the examination of considerable data such as reported in Table II and elsewhere, it appears that the entire magnetization curve when plotted $\mu/\beta^2$ *versus* $\beta$ on log-log paper, can be said to consist of four straight sections joined by three curved sections. Starting with saturation, $\beta$ is constant and $\mu$ continues to rise slowly in value from in the vicinity of unity. The curve is vertical, with the coefficient and exponent infinite in value. The second straight section, between saturation and maximum permeability, yields very large values for the coefficient and exponent. The third straight section, between maximum and approaching initial permeability (the section reported on in this paper) has comparatively low values and covers a large range of flux densities. The fourth section is that which terminates in initial permeability, where $\mu$ approaches a

TABLE III—DATA FOR FIG. 3

| $\beta$ gausses | $\mu$ | $H$ oersteds | $\mu/\beta^2$ | $1/\mu$ | $\mu'$ per cent deviation | $\mu''$ per cent deviation |
|---|---|---|---|---|---|---|
| 100 | 1,000 | 0.100 | 0.100 | $1.000 \cdot 10^{-3}$ | −1.50 | 2.8 |
| 150 | 1,170 | 0.128 | 0.052 | $0.854 \cdot 10^{-3}$ | 4.80 | 32.6 |
| 200 | 1,380 | 0.145 | 0.0345 | $0.724 \cdot 10^{-3}$ | 4.20 | 17.8 |
| 250 | 1,580 | 0.158 | 0.0252 | $0.633 \cdot 10^{-3}$ | 3.16 | 10.5 |
| 300 | 1,780 | 0.168 | 0.0198 | $0.563 \cdot 10^{-3}$ | 1.19 | 12.4 |
| 400 | 2,100 | 0.190 | 0.0131 | $0.476 \cdot 10^{-3}$ | 0.715 | 4.5 |
| 500 | 2,420 | 0.206 | $9.700 \cdot 10^{-3}$ | $0.413 \cdot 10^{-3}$ | −1.24 | 1.85 |
| 600 | 2,680 | 0.224 | $7.450 \cdot 10^{-3}$ | $0.373 \cdot 10^{-3}$ | −1.49 | 0.75 |
| 700 | 2,950 | 0.237 | $6.02 \cdot 10^{-3}$ | $0.339 \cdot 10^{-3}$ | −2.54 | −1.90 |
| 800 | 3,180 | 0.252 | $4.97 \cdot 10^{-3}$ | $0.314 \cdot 10^{-3}$ | −2.51 | −2.50 |
| 1,000 | 3,600 | 0.278 | $3.60 \cdot 10^{-3}$ | $0.278 \cdot 10^{-3}$ | −3.28 | −5.55 |
| 1,500 | 4,440 | 0.330 | $1.98 \cdot 10^{-3}$ | $0.225 \cdot 10^{-3}$ | −1.46 | −1.35 |
| 2,000 | 5,200 | 0.387 | $1.30 \cdot 10^{-3}$ | $0.192 \cdot 10^{-3}$ | −1.54 | −0.96 |
| 2,500 | 5,900 | 0.424 | $0.944 \cdot 10^{-3}$ | $0.169 \cdot 10^{-3}$ | −1.86 | −2.02 |
| 3,000 | 6,470 | 0.464 | $0.720 \cdot 10^{-3}$ | $0.154 \cdot 10^{-3}$ | −1.85 | 0.15 |
| 4,000 | 7,470 | 0.535 | $0.467 \cdot 10^{-3}$ | $0.134 \cdot 10^{-3}$ | −0.268 | 4.40 |
| 5,000 | 8,320 | 0.600 | $0.333 \cdot 10^{-3}$ | $0.120 \cdot 10^{-3}$ | 1.80 | 5.05 |
| 6,000 | 8,800 | 0.682 | $0.244 \cdot 10^{-3}$ | $0.114 \cdot 10^{-3}$ | 6.50 | 16.8 |
| 7,000 | 8,980 | 0.780 | $0.183 \cdot 10^{-3}$ | $0.111 \cdot 10^{-3}$ | 14.4 | 37.2 |
| 8,000 | 8,900 | 0.900 | $0.139 \cdot 10^{-3}$ | $0.112 \cdot 10^{-3}$ | 23.6 | |
| 10,000 | 7,500 | 1.333 | $0.075 \cdot 10^{-3}$ | $0.133 \cdot 10^{-3}$ | | |
| 12,000 | 4,800 | 2.50 | $0.033 \cdot 10^{-3}$ | $0.208 \cdot 10^{-3}$ | | |
| 14,000 | 1,900 | 7.38 | $0.0097 \cdot 10^{-3}$ | $0.525 \cdot 10^{-3}$ | | |
| 14,500 | 968 | 15.0 | $0.0046 \cdot 10^{-3}$ | $1.035 \cdot 10^{-3}$ | | |
| 15,000 | 653 | 23.0 | $0.0029 \cdot 10^{-3}$ | $1.535 \cdot 10^{-3}$ | | |
| 15,400 | 482 | 32.0 | $0.0020 \cdot 10^{-3}$ | $2.080 \cdot 10^{-3}$ | | |
| 16,000 | 320 | 50.0 | $0.00157 \cdot 10^{-3}$ | $3.120 \cdot 10^{-3}$ | | |

The permeability $\mu'$ is that calculated by $\mu' = 78.1\,\beta^{0.55}$; $\mu''$ is that calculated by $\mu'' = 16{,}660\,H^{1.21}$. The per cent deviation shown by the last two columns indicates the difference between the measured permeability $\mu$ and the calculated permeabilities $\mu'$ and $\mu''$ by the relation $100\,(\mu - \mu')/\mu$ per cent. The first two columns, $\beta$ and $\mu$, give the data measured on a good grade of 4 per cent silicon sheet steel.

constant value as $\beta$ approaches zero. For this fourth section, the limiting value of the slope exponent is 2, and the coefficient value becomes very nearly equal to the initial permeability. Table IV lists average values for the coefficient and exponent of the four sections, for good grades of 4 per cent silicon sheet steel.

Considering the three curved sections, it has been observed and shown in Fig. 2 that in general the radius of curvature is less for the curved section containing maximum permeability than for the curved sections on either side. In several sets of data there was a slight indication of a short flat $S$ shaped section in place of the curved section terminating in saturation.

As the $\mu/\beta^2$ ordinate also represents $1/\beta H$ and $1/\mu H^2$ (see (**1a**)), the flux density is also a function of the magnetizing force $H$. From the general shape of the whole curve, there appears to be four distinct phases of magnetization obeying definite laws of the same form, which are represented by the straight sections of the curve when shown on log-log paper. Also, there are three transitional phases as represented by the curved sections, for which expressions have not been derived. Although these four phases of magnetization can be observed in a general way from the usual $\beta - H$ curve, it is not obvious they follow apparently similar laws.

Starting with very low values of $H$, it can be conceived that a small number of loosely bound magnetic units exist that can be oriented in the same direction by weak magnetizing forces, following a definite law. As $H$ increases, passing the first curved section, a range of values is reached which is capable of orienting the majority of the units. This is the range reported by this paper. There still exist a goodly percentage of the units more closely bound and it requires much greater values of $H$ to orient these with the others. This gives the straight section preceding saturation. Lastly, all have been oriented and saturation exists, this straight section extending onward with increased values of $H$ and decreased values of $\mu$. For some materials there may exist the small secondary transition section terminating in saturation, as mentioned above.

TABLE IV—AVERAGE VALUE OF COEFFICIENT AND EXPONENT FOR THE FOUR SECTIONS OF THE MAGNETIZATION CURVE FOR 4 PER CENT SILICON SHEET STEEL

| Section of curve | $P$ | $M$ | Equation |
|---|---|---|---|
| 1. Saturation | $\infty$ | $-\infty$ | $\mu/\beta^2 = \infty/\beta^{\infty}$ |
| 2. Between saturation and maximum permeability | $1 \cdot 10^{51}$ | −14 | $\mu/\beta^2 = 1 \cdot 10^{51}/\beta^{14}$ |
| 3. Between maximum permeability and approaching initial permeability | 80 | −1.5 | $\mu/\beta^2 = 80/\beta^{1.5}$ |
| 4. Vicinity of and including initial permeability | 375 | −2.0 | $\mu/\beta^2 = 375/\beta^2$ |

Note: For section No. 4, $M$ has a limiting value of two; the actual value may be slightly less than two.

Experimentally to prove this hypothesis concerning the definite steps in complete magnetization of a material, it will be necessary to examine carefully a large number of samples over the entire range of the magnetization curve. The available data have indicated that this process apparently exists, at least within the limits of accuracy of plus or minus 1 per cent; consequently the author presents these findings for further consideration.

### CONCLUSIONS

In conclusion, the following summary may be stated:

1. An equation of the form: $\mu = P\,\beta$ has been derived experimentally which closely reproduces the flux density-permeability curve for magnetic materials of various compositions and quality, in the flux range of approximately 80 to 6,500 gausses.

2. The coefficient $P$ and exponent $a$ are determined from the data by graphical and analytical means, both being influenced by the nature of the material, with the former being indicative of the relative value of the initial permeability.

3. An extension of the method to other portions of the magnetization curve, indicate three other regions which can be expressed by similar equations.

4. Theoretical considerations of the entire magnetization curve as given by $\mu/\beta^2$ *versus* $\beta$ on log-log paper, indicate that there are four distinct phases of magnetization coupled by three transitional phases. Each of the four phases may be given by the general equation: $\mu = P\,\beta^a$, with $P$ and $a$ having different values.

5. The degree of accuracy in obtaining these empirical equations is sufficient for most commercial design purposes to allow their use in calculation over the flux densities for which they hold, without reference to the $\beta - H$ curve.

6. The data plotted as $\mu/\beta^2$ *versus* $\beta$ for the entire range of the magnetization curve are useful for certain design procedures where it is desirable to obtain $\beta$ for various values of $\mu/\beta^2$, which frequently appears in certain methods of design.

### ACKNOWLEDGMENT

The author wishes to express his appreciation to Professor J. H. Kuhlmann of the University of Minnesota, for a preliminary reading of the paper; to Mr. R. L. Sanford, of the Bureau of Standards, for certain comments on the method involved; to Mr. S. L. Gokhale, for the use of data from his paper[1]; to the American Rolling Mills Company and the Follansbee Brothers Company, for permission to use data from several of their published curves; and to Mr. N. S. Neilson, for his kind assistance in operating the laboratory equipment and taking data on numerous samples of sheet steel.

## Appendix

The general equation $Y = PX^M$ can be expressed in logarithmic form as

$$\log Y = \log P + M \log X \qquad (2)$$

Equation (2) is of the form $Y = P + MX$ which is the equation of a straight line when plotted on coordinate paper. The coefficient $M$ in (2) or exponent $M$ in (1) is obtained on either the coordinate or log-log papers, respectively, by linear measurements, as $M$ is the slope of the straight line. The intercept $P$ is obtained by extension of the straight line to intersection of the ordinate for $X = 1$.

Generally, the slope $M$ can be more accurately measured than the intersection of the ordinate $P$ by extension of the line graphically. By the several methods available for drawing in the mean straight line through the data points, the slope can be determined by measurements or by calculations. Then by using values for $X$ and $Y$ taken from the curve or data, the value of $P$ can be calculated. This procedure is sufficiently accurate for most design purposes. The equivalent designations for $X$ and $Y$, for the specific case at hand, are $\beta$ and $\mu/\beta^2$, respectively, and the equations can now be thrown into any form desired.

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## Discussion

**G. H. Cole:** The Barton method of extrapolating data to a very low induction should be very useful in correlating a-c and d-c tests on materials intended for radio applications. Most d-c permeameter methods suitable for accurate determinations of permeability at high induction are not sufficiently sensitive for low induction work. On the other hand, a-c methods of permeability measurement are usually inaccurate at moderate and high inductions, due to the difficulty in determining the peak value of the a-c wave. By means of the Barton equation, these can now be correlated. Evidently, no appreciable difference exists between the two types of tests judging by the checks which are reported in the paper.

Our experience indicates that the permeability at inductions of 100 gausses or less is the best criterion of quality of electrical sheet steel used in certain radio receiver applications, such as audio transformers. The methods given in the paper for extrapolating magnetization data into this range should be convenient and helpful. For the above-mentioned application our experience has been that it is not necessary to determine the permeability for inductions of less than 1 gauss, and hence determinations of $P$ in equation (**1b**) can be used as the initial permeability.

**S. L. Gokhale:** About 5 years ago, that is, shortly after the publication of my *Law of Magnetization*, (A.I.E.E. Trans., Vol. XLV, June 1926, p. 1013) our laboratory started to extend our study to the lower part of the magnetization curve. We found the Baur's Law ($\mu = aH + b$), which had already received confirmation from Raleigh, approximately but not strictly correct. We tried also an equation of the form $\beta = aH^b$, and did not have much success. Mr. Barton's paper is, therefore, a great surprise to me, because his equations $\mu/\beta^2 = P\beta^{-m}$ and $H = \beta^c/P$, merely are two other forms of the equation $\beta = aH^b$ which did not appeal to me as very promising. Mr. Barton's success with the same equation suggests among other possibilities the possibility that I might have overlooked something.

Mr. Barton has used an imperfect magnetic circuit with strips; with proper precautions to minimize the effect of this imperfection, and has also used a 60-cycle alternating current. We had used toroid rings and direct current, and it seemed at first that this difference in the methods made the difference in the result. But Mr. Barton has successfully extended his equation to our data, which makes it necessary to look for an explanation somewhere else.

As to the several phases in the progress of the magnetization curve, this same conclusion had been reached by the Bureau of Standards (Scientific Paper No. 404, p. 741).

**Hans Lippelt:** This paper embodies a study of magnetization curves and their evaluation in search of a mathematical term which would relate the magnetizing current to the magnetic flux. As a solution a simple formula $\mu = P\beta^{\alpha}$ is offered as the result of reported experiments with alternating current.

The author also follows precedent when defining $\mu = \dfrac{\beta}{H}$ not $\dfrac{B}{H}$.

As stated in the paper, the relation is empirical, and I wish to go a step further by saying that the quantity $\mu$ in itself is an empirical quantity. This applies notwithstanding the fact, that we have assigned to $\mu$ the good and descriptive name permeability, which, it is conceded, defines $\mu$ as a property of the material. (See explanation given in the paper after quoting formula (**1**).)

It is my contention that this property of the material is not retained in its virgin state as the progress of magnetization goes on. It is interfered with by physical reactions such as set up by hysteresis, temperature and mechanical stress.

The erratic character of $\mu$ will readily be recognized by an inspection of Table IV, which discloses that the "constants" $P$ and $\alpha$ of the fundamental formula vary very greatly over the full range of magnetization.

It seems after all that a quantity

$\nu = \dfrac{\beta}{R}$ where $R$ ($- R$ to be correct) represents that part of $H$, which is available for magnetization proper has more justifition, than $\mu = \dfrac{\beta}{H}$ or $\dfrac{B}{H}$. Compare herewith A.I.E.E. Trans., February 1926, p. 395 under paragraph 2*b*; and also p. 396, equation (2).

The author of the paper refers repeatedly to Mr. Gokhale's paper on the *Law of Magnetization*. The latter is given as

$$\beta = S\,(1 - be^{-\alpha H})$$

and is said to apply for the region near saturation. Mr. Barton states further that Gokhale's equation very closely reproduces the curve of $\dfrac{\mu}{\beta^2}$ as shown in Fig. 2 of his paper, but he does not undertake to prove that

$$\frac{\mu}{\beta^2} = \frac{1}{H\beta} = PB^{-M} \text{ is equivalent to } \frac{1}{HS-(1be^{-aH})}$$

as proposed

a sequence to Gokhale's equation

$$\text{or } \frac{1}{P}\,\beta^{M} \text{ equivalent to } HS\,(1 - be^{-aH})$$

a proof which would greatly enhance the author's work.

While explaining Fig. 2 of his paper, the author speaks of the "second straight part," situated between Kennelly's and Yensen's range. He also asserts that this second straight part (and the third) is well covered by Gokhale's equation. But just for this "second part" Gokhale admits that Frolich's Law applies. (See A.I.E.E. Trans., June 1926, p. 1023, section 19, paragraphs 8 and 7, *a* and *b*.) It does not seem plausible that the law of magnetization should change in the short interval *between* the two regions cited. In the introduction to the paper it is claimed that Frolich's Law is not reliable. A conclusive statement should be presented.

Referring now to Fig. 3 of the paper and corresponding text: if the author asks for an answer as to why the "two straight lines" of the reluctivity curve intersect for $\mu = \mu_{max}$, he will probably find it by:

1. Observing what the writer set forth in his own paper on the *Magnetic Hysteresis Curve*, A.I.E.E. Trans., 1926, p. 406, Chapter VII in connection with Fig. 14.
2. Observing, as stated at the beginning of this discussion, that $\mu$ is an erratic quantity and should be replaced by $\nu = \dfrac{\beta}{R}$.
3. That when taking note of hysteresis

$$\mu = \infty \text{ when } H = 0, \text{ namely } \mu = \frac{\text{Remanent magnetism}}{H \text{ (which is zero)}}$$

$$\mu = 0 \text{ when } H = \text{coercive force } \mu = \frac{\text{Zero magnetization}}{\text{Coercive force}}$$

and that this coercive force depends on the highest value of $\beta$ obtained under the a-c cycle.

4. That by using alternating current, these important characteristics, remanent magnetism and coercive force, are removed from observation and cannot provide premises for a conclusion such as is sought.

That an exponent (like $\alpha$) may be attached to magnetic quantities (as $\beta$ for instance), when the law of magnetization is finally established, is indicated also in the discussion printed in the A.I.E.E. Trans., 1926, p. 412, equation (e).

In order to unveil the law of magnetization, as it applies between positive and negative saturation, the *complete physical state* of the material (and its changes during the process) should be taken into consideration, to wit: molecular friction (hysteresis), temperature and mechanical stress.

Ewing has written a book on the influence these physical states have upon the process of magnetization (see the references to this on page 413 of the aforestated reference). When truly observed they will illuminate the author's conclusion No. 4.

**A. C. Seletzky:** Over the range of introduction studied, Mr. Barton has discovered an empirical relationship, which for practical purposes connects the values of induction and magnetomotive force with a reasonable degree of accuracy. The value of the expression as experimentally determined, $\mu = PB^{\alpha}$, is however seriously undermined when considered theoretically because both sides of the formula do not have the same dimensions. Although the dimensions of $\mu$ itself are not known, its role as a factor in the expression $[k\mu]^{-1/2} = v$ is well established; ($k$ = dielectric constant, $v$ = velocity of light). Hence whatever the dimensions of $\mu$ might be, they must remain constant for all magnetic materials, if the dimensions of the dielectric constant remain fixed. The expression of Mr. Barton, $\mu = PB^{\alpha}$, admitting a variable exponent gives a different dimension for $\mu$ with every distinct value of $\alpha$ since $P$ is a numerical constant. From Table II in the paper, this exponent under the column heading $(2 - M)$ varies from 0.290 to 0.758.

The expression obtained by Gokhale, $B = S\,(1 - be^{-aH})$, although open to a number of weighty objections based both on theoretical and experimental evidence, as has been pointed out by Sanford,[1] does at least have the same dimensions on both sides of the equality sign. Hence in time, it may be modified without changing its form. I do not wish to detract in any way from the practical significance of Mr. Barton's findings, but merely to point out that if any considerable headway is to be made into the determination of the functional relationship existing among magnetic quantities, that it is necessary to start with expressions which at least satisfy the law of dimensions. Thus, I venture to propose that Mr. Barton make an attempt to throw his expression into another form which will satisfy this condition; before this is done it is useless to read any physical significance into any of the constants of the formula as it now stands.

**A. C. Schwager and V. A. Treat:** The general use of log-log paper is advocated for the analysis of magnetization curves and the advantages gained thereby are pointed out. The author is to be complimented for bringing these facts to the general attention, if they are utilized they will result in great advantage wherever they can be applied.

This will be shown for one specific case, the current transformer. It is well known that current transformers operate in the range of low flux density. The usual method is to plot on log-log paper, the reactive voltamperes per pound of the core material in relation to the flux density. T. D. Yensen has shown such a relation for silicon iron and nickel iron (permeability of hypernik reaches 167,000, *Electrical World*, June 1931). From Fig. 6, it is seen that the rva per lb, over a wide range are approximated by a straight line, resulting in rva per lb = $B^{1.6}$. The expression for magnetizing current then immediately follows:

$i_m = cB^{0.6}$ and the permeability $u = d\dfrac{B}{i_m} = eB^{0.4}$, the last relation having been illustrated on log-log paper by Keinath, *ETZ*, 1932, p. 1596. We have made use of this relation to express analytically the performance of current transformers over their normal operating range.[2,3] In this manner the variation of the phase angle with the secondary current of a specific transformer with a secondary burden $r$ and $N$ secondary turns can be represented by:

$$\theta = \text{const.}\,\frac{r^{0.4}}{N^{1.6}\,I_2^{0.4}}\ \text{minutes.}$$

The usual time consuming method of calculating transformer characteristics point by point thereby is eliminated. The application of Frolich's Law, or of the formula given by the author for high flux density, furnishes formulas for the overload characteristics.

The advantages which result from this procedure in the case of current transformers, apply to any other magnetic circuit, and it is hoped that Mr. Barton's paper will further point out the benefits of such a method.

**James P. Barton:** The writer has not had the opportunity to demonstrate Mr. Cole's suggestion, but as equation (1) reproduces satisfactorily the intermediate range of the normal magnetization curve from data taken by the d-c ring permeameter and the a-c strip bridge methods, it is felt that measurements on the same sample by the two methods, properly conducted, should be joined by equation (1). If reasonable assurance is to be had that the magnetic circuit conditions are equivalent to each other for the two standard methods, then the values for the coefficient and exponent should very closely agree. The sample should be thoroughly demagnetized before each run, and probably for best results the values of $H$ should be increased from minimum to maximum.

Mr. Gokhale's reference to the *Bureau of Standards Scientific Paper No. 404*, on the several phases in the progress of magnetization, discloses a general and obvious division of the curve into three parts, the divisions occurring in the foot and knee sections of the magnetization curve but not in a well defined manner. The procedure given in this paper under discussion allows a definite division of the curve into the several phases, as they are expressed by equations whose graphs intersect, forming definite divisional points.

It is surprising to learn that others have considered equations of similar form for the same range covered as disclosed in this paper, but not surprising to note that Mr. Gokhale's laboratory did not arrive at satisfactory results upon consideration of this method. The writer is greatly interested in this and would be glad to learn of any conclusions as to where the difference lay.

It is possible that precise measurements may disclose greater deviations than shown, although the curves drawn to published data taken under presumably carefully controlled conditions yield no greater deviations from the calculated curve than for what we may term commercial grade measurements. Because of the apparently consistent performance of the method when tried with data obtained by various methods and degrees of accuracy, it was felt to be possibly of more value than just for design purposes. Thus the urge for the procedure to be investigated further.

Mr. Lippelt's comments on permeability express the writer's feelings in that when it is said a sample has a certain permeability, we must go further than that single statement, if that value is to be of use to us. The value of $\mu$ depends so much on the history of the sample as well as its physical state at the time of measurement, that it is felt many sins are committed in its name. In connection with the effect of hysteresis, the writer did not have any satisfactory data at hand for testing equation (1) on the branches of the loop.

Referring to Fig. 2 of the paper, Gokhale's equation is of such a form that it covers the range preceding and including saturation with a smooth curve, whereas when expressing the curve as $\beta$ *versus* $\mu/\beta^2$, this same region appears as two straight lines joined by a curved section. In reproduction of the data by both equations, there is close agreement over the common portion, but I do not know which one, including Frolich's, more nearly expresses the true law of magnetization.

All of the attempts at the law of magnetization undoubtedly are building stones for the structure that eventually will house that law. The work entailed in determining the limits of application and the testing of these attempts is truly tremendous, because of the great variety of materials to be covered as well as the variable physical and chemical states of these materials. This is emphasized by the fact that many have limited themselves to certain portions of the curve for a continued study, which for most of the equations has been in the neighborhood of saturation.

This paper was presented only after it was reasonably well shown that equation (1) held over the intermediate range of the normal magnetization curve, when commercial and laboratory data were used as measured on various materials in random physical states. The theoretical discussion briefly was limited only to what appears to be the first division of the normal magnetization curve into segments each expressed by equations of the same form, providing natural divisional points at the intersection of their graphs.

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[1] "Magnetic Reluctivity Relationship," Sc. Papers of Bureau of Standards, No. 546, Vol. 21.

[2] *Shaping of Magnetization Curves and the Zero Error Current Transformer*, by A. C. Schwager and V. A. Treat, A.I.E.E. TRANS., March 1933, p. 45.

[3] "Der Fehlerlose Stromwandler," by A. C. Schwager. *Bulletin des Schweizerischen Elektrotechnischen Vereins*, Nov. 20, 1932.

# The Dielectric Losses in Impregnated Paper

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***Synopsis.**—Accurate measurements have been made of the electrical and other physical properties of 10 insulating oils, of a single grade of wood pulp paper, and of the paper when impregnated with each of the oils. Short time charge and discharge curves under continuous potential have thrown further light on the anomalous conduction as found in oils, and permit the separation of the total dielectric loss into two components.*

*Of the total increase of the loss found in impregnated paper, over the separate losses in oil and in dry paper, one component is proportional to the effective conductivity of the oil. The other component, due to reversible absorption, is, for a given paper, a definite function of the free ion content of the oil as indicated by the product of the conductivity by the viscosity. These relations hold over the entire ranges of type of oil and temperature under study.*

*The product of conductivity by viscosity is proposed as a measure of the "electrical purity" of an oil used for impregnation.*

*The simplicity of the relations shown suggests that an extension of these studies to other grades of paper should make it possible to predict accurately, from the separate properties of paper and oil, the electrical behavior of any grade as impregnated with any type of oil.*

* * * * *

## INTRODUCTION

By the sufficient refinement of the oil and the paper, and by careful elimination of air and moisture, the dielectric losses in impregnated paper may be reduced to very low values. Thus, at ordinary temperatures, values of the power factor of the dielectric in high-voltage cables and in impregnated paper condensers may be had within the range 0.001 to 0.003. This means that under most conditions the losses in the dielectric in high-voltage cables are relatively small as compared with those in the conductor, and so do not seriously limit the current carrying capacity of the cable as related to the rise of temperature of the insulation.

On the other hand, the dielectric losses in cables commonly increase in service, and the relation of these changes to the stability of the insulation and the life of the cable is one of the most important problems confronting the manufacturer and user of cables of this type. Little is known as to the relation between the dielectric loss of impregnated paper and the separate losses in the constituent oil and paper. It is generally known that the lower the conductivity and power factor of the oil, the lower the resulting loss in the impregnated paper, and it is also known that the loss in the impregnated paper is generally substantially greater than the joint losses in oil and paper separately. Quantitative relationships, however, have never been established, largely due to the fact that until recently, the possible measurements have been limited to those of alternating loss and power factor, and of conductivity under continuous potential. Owing to the complexity of the materials and the number of factors entering, satisfactory correlation and prediction of final losses have not heretofore been possible. The predetermination of the electrical behavior of a complex dielectric, in terms of the behavior of its constituents is one of the most obscure problems in the whole field of dielectric behavior. The reason for this is found in the fact that no single insulating material, however carefully refined and prepared, possesses the characteristics of an ideal dielectric, which should show only specific inductive capacity. We have in Maxwell's theory a very satisfactory explanation of the a-c behavior of complex dielectrics of which the constituents possess only inductive capacity and conductivity. However, few if any available insulating materials satisfy even these simple conditions. As a consequence, while many complex dielectrics approach the behavior predicted by theory, in general the agreement is roughly qualitative only. In particular, in the case of insulating oils and cellulose paper, each of these materials is so complex in its dielectric properties that, to the experimenter, it is almost immediately obvious that a quantitative agreement with any theory of dielectric loss cannot be expected from the studies of the behavior of the paper when impregnated with the oil.

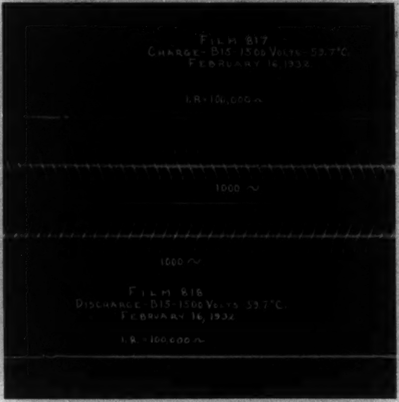

FIG. 1

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

Nevertheless, although a convincing theory and experimental agreement therewith may not be expected, it is yet entirely possible to study more closely and with careful quantitative measurements, the behavior of these substances separately and in combination, and to examine the results to see if any correlation is possible between the original general physical properties of the constituent materials and the dielectric losses of their combination. In this paper we are reporting some studies of this character. The general plan has been to adhere as closely as possible to one type of paper, to vary the oil over as wide a range of types as possible, to study the electrical and other physical properties of each, and the electrical properties of their combination, over the range of temperature 25 deg to 65 deg, this being the important range of cable operation.

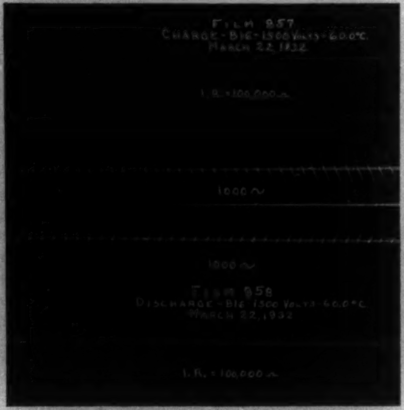

Fig. 2

## Experimental Method

The test specimens were in the form of cylindrical capacitors. The central high-voltage electrode was a brass tube 5.8 cm outside diameter, 61 cm long, on which 0.1 mm thick wood pulp paper was spiralled as in impregnated paper cables, with butt joints between tapes, and to a depth of 15 layers. The outer electrode was of sheet lead and provided with guard electrodes. For the oil a second capacitor of approximately equal dimensions was used. Each capacitor was mounted in a separate constant temperature vacuum tank. The oil was thoroughly degassed by spraying into a vacuum, and the paper thoroughly dried by heating under vacuum. After the measurements on the oil were made, the oil was drawn under vacuum into the tank containing the paper capacitor, impregnating the latter without intervening exposure to air.

Electrical measurements were made under both alternating and continuous voltage. Dielectric loss, power factor and capacitance, as related to temperature between 25 deg and 65 deg C, were measured at 60 cycles over the range 500 to 1500 volts effective values, on a high sensitivity Schering bridge. The measurements under continuous voltage were the short and long time values of charge and discharge currents and the irreversible absorption, initial and final conduction, as deducible therefrom. Charge and discharge currents beginning one millisecond after the application of voltage or of short circuit were read, using the amplifier oscillograph. This instrument increases the normal sensitivity of the electromagnetic oscillograph $10^5$ times giving a deflection on the photographic film of 1 mm per $4 \times 10^{-8}$ amp.

The short time charge and discharge curves, as read on the amplifier oscillograph, are an essential feature of the present work. They show that the conductivities of both oil and paper for the time intervals comparable with the alternating cycle are, in general, functions of the time and of markedly different values to those pertaining to longer time intervals. Moreover, as we have

TABLE I—PHYSICAL PROPERTIES OF IMPREGNATING OILS

| Specimen | Base | Flash point °F | Pour point °F | Density (A.S.T.M.) Specific gravity | Degrees baumé | Viscosity (A.S.T.M.) seconds saybolt 100°F | 130°F | 210°F |
|---|---|---|---|---|---|---|---|---|
| B 4<br>B 6<br>B 7 | Midcontinental crude | 525 | 90–100 | 0.89 | 27.0 | 2,350 | 830 | 130 |
| B 8 | Highly refined water-white oil | — | 32 | 0.85 | 36.0 | 85 | 60 | 38 |
| B10 | Dewaxed mid-continental crude | 540 | 20 | 0.90 | 25.5 | 2,935 | 940 | 154 |
| B13 | Semi-refined napthene | 550 | 20 | 0.94 | 19.1 | 4,100 | 1,400 | 147 |
| B14 | 3:1 mixture by wgt. of rosin and B10 | — | 40 | 0.95 | 17.0 | 10,070 | 2,910 | 240 |
| B15<br>B16<br>B17 | Similar to oil B10 certain unstable hydrocarbons removed | 505 | 40 | 0.90 | 23.0 | 2,010 | 745 | 120 |

shown in an earlier paper,[1] these short-time current curves may be used to predict accurately the alternating current loss, through the empirical derivation of the equations of the curves and the application of the method of von Schweidler. This method of analysis and the separation of the irreversible or conduction component, from the reversible or absorption component of the loss, which it permits, is also an essential feature in the studies reported in this paper.

For a more complete description of the specimens and their method of assembly for the measurements, and particularly for a description of the method of analyzing the oscillograph records, and computing the losses, the earlier papers[1,2,3] may be consulted.

In the following description of the results, the dry paper specimens are designated by the letter A, oil specimens by the letter B, and impregnated specimens by the letter C, a numeral following in each case. The same numeral applies to the component paper and oil of the corresponding combination. For example A-8 and B-8 are combined to form C-8.

CHARGE - B17 - 1500 VOLTS - 60.1°C.
MAY 2, 1932
R = 20,000 Ω
1000 ~
1000 ~
DISCHARGE - B17 - 1500 VOLTS - 58.6°C.
APRIL 26, 1932
R = 100,000 Ω

FIG. 3

## THE OILS

In Table I are given brief descriptions and the principal physical characteristics of the 10 different samples of oils which have been studied. The oils were furnished by four different well known manufacturers of insulating oils. All of them except B-8 and B-13 are those oils commonly spoken of as being of paraffin base. B-4, B-6, and B-7 are three samples of the same oil, in the original condition, and in two stages of deterioration by oxidation. The results with these three oils have been described in some detail in the paper[2] by Whitehead and Kouwenhoven, cited above. A similar relation exists among the three samples, B-15, B-16, and B-17. B-10 is a well known oil for solid cables and in B-14 it is mixed with rosin (abietic acid) in the ratio 3:1. B-8 is a highly refined very thin white oil whose basic nature is not given. B-13 is a semi-refined oil of naphthenic base. As will be seen, the group presents a fairly wide range of viscosity.

*Conductivity.* Typical short time charge and discharge current curves, as observed with continuous voltage are shown in Figs. 1, 2, and 3, for oils B-15, B-16, and B-17. Additional examples of these curves and the methods of deriving the equations for oil B-7 are given in the Whitehead and Baños paper.[1] The results for the principal oils of the group here studied have been plotted from the oscillograms on double logarithmic scales in Fig. 4. These results show that a principal characteristic of all these oils is an initial conductivity which, in most cases, has a constant value over a period of one second. Thereafter the current falls off more or less rapidly and this initial constant conductivity in some cases may be several hundred times as high as the conductivity measured say after a minute or more. More commonly, however, this ratio is much lower as shown in Table II. The tendency of increasing conductivity, either as the result of oxidation or temperature elevation, is to lower the ratio of the initial to the final conductivity. For example, in oil B-17, with conductivity increased some 250 times by oxidation, the conductivity at $10^4$ seconds differs very little from the initial value during the first one second. The variation with temperature of the initial constant conductivity is shown in Fig. 5. This conductivity is independent of the voltage in the range studied, with some indication of an increase with voltage for temperatures above 60 deg.

TABLE II—COMPARISON OF OIL SPECIMENS
Variation with Temperature of Ratio $\lambda_i/\lambda_f$, Initial Constant Conductivity $\lambda_i$ to 40-Min Conductivity $\lambda_f$ at 1,500 Volts D-C

| Specimen | Ratio: $\lambda_i/\lambda_f$ | | |
|---|---|---|---|
| | 30 deg C | 45 deg C | 60 deg C |
| B15 | —* | —* | 7.01 |
| B 8 | 500.00 | 593.00 | 215.00 |
| B 6 | 7.23 | 7.18 | 4.59 |
| B14 | 1.17 | 1.09 | 1.24 |
| B10 | 4.08 | 4.18 | 4.22 |
| B16 | 2.71 | 2.25 | 2.05 |
| B 4 | 10.43 | 7.00 | 4.45 |
| B 7 | 7.29 | 5.33 | 4.02 |
| B17 | 1.79 | 1.70 | 1.45 |
| B13 | 1.77 | 1.56 | 1.49 |

*$\lambda_i$ too small to detect.

Oils B-7, B-8, and B-15 all show an initial decaying value of charging current over the interval of the first few thousandths of a second, as already reported in an earlier paper.[1] This phenomenon in the case of B-7 seems to be of the nature of reversible absorption since it is accompanied by a discharge curve on short circuit of similar character. Under certain circumstances, the discharge curve seems to be exactly equal and opposite to that portion of the charging current curve which lies above the longer initial horizontal portion. In other cases (B-8 and B-15) the corresponding short initial discharge seems to be absent. In general this initial brief current decay seems to be more pronounced in the lower conductivity oils (B-8 and B-15), although it also appears in slight measure in oil B-7 of much higher conductivity. This feature of the curves is also usually obscured by increasing conductivity, as shown in the earlier paper for oil B-7 with increasing temperature, and here for oils B-16 and B-17 with increased conductivity due to oxidation.

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[1] For references see Bibliography.

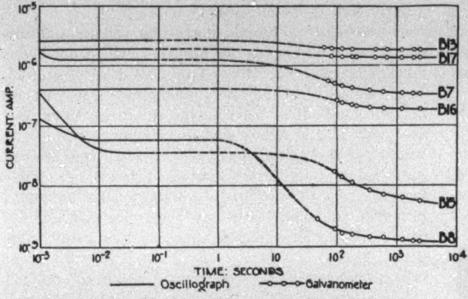

FIG. 4—COMPARISON OF OIL SPECIMENS

Variation with time of charge current at 1,500 volts, 60 deg C

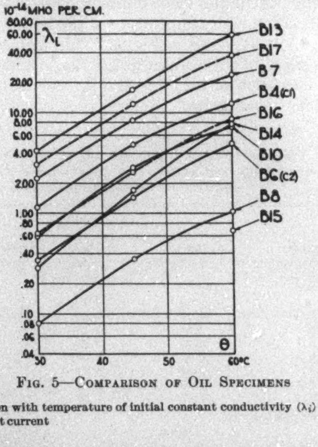

FIG. 5—COMPARISON OF OIL SPECIMENS

Variation with temperature of initial constant conductivity ($\lambda_i$) at 1,500 volts direct current

It is possible that this initial absorption is present to some extent in all oils of these classes. We have found that when it is not present on the oscillograms, the alternating loss is completely accounted for by the conductivity as determined from the initial horizontal or constant-current value. On the other hand, when the initial absorption is present, due account must be taken of it in computing the a-c losses from the d-c characteristics as described in the earlier paper.[1]

The discharge curves are of great interest. So far as their initial sharply decaying region is concerned, they seem to indicate that liquids may show dielectric absorption, for which there has been no evidence heretofore. The later regions of the discharge curve show a very much more gradual decay and are probably associated with the slow movement of space charges carried by larger types of ion.

*Power Factor and Loss.* The power factor temperature relation for the oils is shown in Fig. 6, the electric field intensity being 10,000 volts per cm (approximately 25 volts per mil). The general correlation as between the initial constant conductivity, as shown in Fig. 5, and power factor, is evident as shown in Fig. 6. In all cases except those showing initial decaying charging current large as compared with the subsequent constant value, the latter accounts completely for the dielectric loss. An exception is to be noted for the oil B-14. This is the 3:1 oil-rosin mixture. The minimum in the power factor-temperature curve for this oil, marks the temperature region in which the viscosity is changing rapidly. In this state, the power factor is due almost entirely to dielectric absorption, the contribution of the initial constant conductivity becoming less and less; at 30 deg it cannot be measured. The power factor-temperature relations for oil B-10 and rosin B-9, which in combination form the oil B-14, are shown in

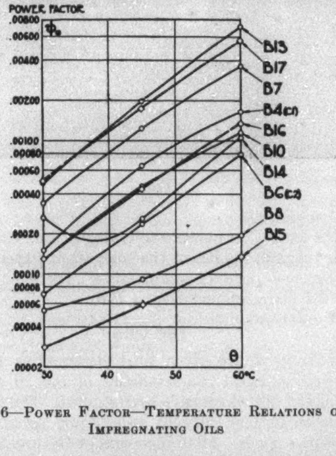

FIG. 6—POWER FACTOR—TEMPERATURE RELATIONS OF IMPREGNATING OILS

Fig. 7. Values of dielectric loss as related to power factor, as measured and as computed from the continuous current charge and discharge curves for oils B-6 and B-7 show[3] that the initial constant conductivity together with the initial absorption (if present) account completely for the total loss.

*Conductivity and Viscosity.* The conductivity of dielectric liquids is ionic in character and the value of the conductivity depends on the number of ions present and on their mobilities or specific velocities. For ions of a given size the mobilities are in general, inversely proportional to the viscosity. This relationship is shown for the various oils under study in Fig. 8 in which are plotted the variation with temperature of the viscosity $\eta$ in poises, and the conductivity $\lambda_o$ in mhos per cm. For convenience, we have used the effective conductivity, assuming that the loss is wholly due to conduction. As already stated, this effective conductivity $\lambda_o$, is identical with the initial constant conductivity as taken from the short time continuous current charging curve, in all oils except those showing appreciable brief initial decay of charging current. In Fig. 9 are plotted the variation with temperature of the product $\eta\lambda_o$ of viscosity and effective conductivity. It will be noted that this product for each oil is roughly constant over the range of temperature 30 deg to 60 deg. Since the conductivity is directly proportional to the number of ions present and inversely proportional to the viscosity, the product $\eta\lambda_o$ is an indication of the number of free ions present. We have then, in this product, a property of the oil which is independent of the temperature. It will be seen that the oils differ markedly as related to the value of this quantity. Obviously, it is not to be expected that the value of $\eta\lambda_o$ should remain constant over any very great range of temperature. In the lower range, as the oils tend to stiffen, it is probable that the inverse relationship between mobility and viscosity does not hold. In the upper range of temperature it is probable that further new ions are generated. The interesting feature here is that we have a quantity which is more or less constant over the operating range of temperature for any one oil and the values of which, over the different oils studied, vary through quite a wide range. We may think of the number of free ions present as to some extent a measure of the purity of the oil. Thus the oil B-8 is probably the most carefully refined of all the oils studied. In contrast with it is oil B-15. The latter oil has a lower value of effective conductivity than oil B-8, yet it is seen that the number of free ions

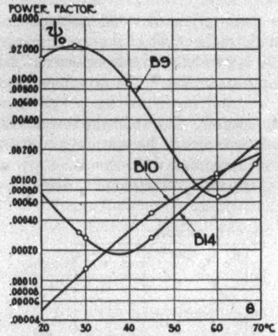

FIG. 7—VARIATION OF POWER FACTOR WITH TEMPERATURE

For rosin (B9), oil (B10) and their 1:3 mixture (B14)

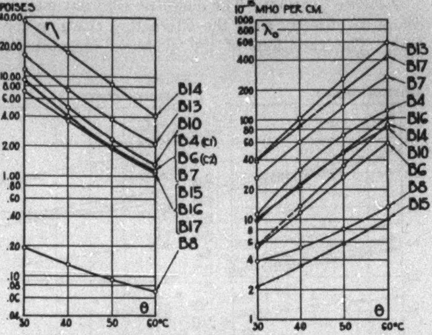

FIG. 8—VARIATION WITH TEMPERATURE OF VISCOSITY ($\eta$) AND EFFECTIVE CONDUCTIVITY ($\lambda_o$) OF IMPREGNATING OILS

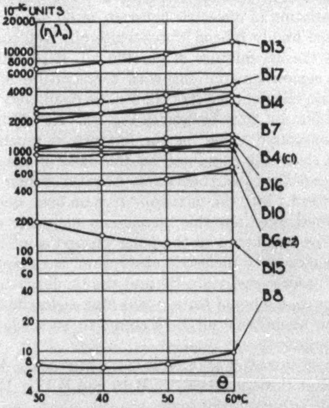

FIG. 9—VARIATION WITH TEMPERATURE OF THE PRODUCT OF VISCOSITY AND EFFECTIVE CONDUCTIVITY ($\eta\lambda_o$) FOR THE IMPREGNATING OILS

present, as indicated by the product $\eta \lambda_o$ is many times greater than that pertaining to oil B-8. This difference is reflected in other ways. We shall in fact, see later on, that this quantity has a direct relationship to the losses in the impregnated paper.

*Dielectric Constant.* The dielectric constant may be computed directly from the alternating charging current. The variations of the dielectric constant $K_o$, and also of the specific gravity $\rho$ for all of the oils studied are shown in Fig. 10. It will be noticed that in general, the variation of the dielectric constant with temperature and as among the various oils, follows the variations in density as it should. The extreme range of variation of dielectric constant at 60 deg is from 2.1 for the highly refined water-white oil, B-8, to 2.48 for B-14 the 3:1 mixture of paraffin oil, B-10, with rosin. The separate variations with temperature of the dielectric constant for this oil, for the rosin, and for their combination, may be seen in Fig. 11. As will be noted, the measured value for the mixture is much greater than the value computed on the basis of the separate values of the constituents and the ratio of their volumes as entering into the mixture. It is an open question as to whether or not this increase in dielectric constant is to be attributed to the polar properties of the rosin molecules or to dielectric absorption as caused by the greatly increased viscosity and the tendency to a solid rather than a liquid state.[4] The high dielectric constant of the naphthenic oil B-13 seems to be accounted for by its density.

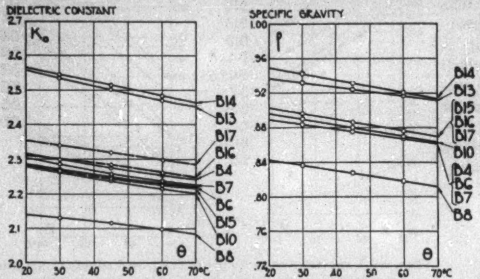

FIG. 10—VARIATION WITH TEMPERATURE OF DIELECTRIC CONSTANT ($K_o$) AND SPECIFIC GRAVITY ($\rho$) OF IMPREGNATING OILS

Another matter of interest is the increase in dielectric constant through oils B-15, B-16 and B-17. These oils are all originally the same, the first B-15, in pure degassed condition and B-16 and B-17 oxidized by bubbling with air at high temperature (105 deg C). It will be seen that this process of oxidation has resulted in an increase of the dielectric constant. There is no corresponding change in either the density or the viscosity of these three oils, and so the increase in dielectric constant must be attributed to other causes. A possible explanation would be a polarized condition of the carbon particles formed by oxidation, as the result of an unsymmetrical adsorption of ions, or a similar behavior as a result of the appearance of colloidal properties. If either of these explanations is correct, the phenomenon should be reflected in the charge and discharge current oscillograms as an initial decaying charge or discharge current. Such curves actually have been observed as indicated above. On the other hand, it is possible to compute from the observed curves the contribution of these initial decaying portions to the final measured dielectric constant. Such computations indicate that the contribution to the total dielectric constant is very much smaller than the actual change in values reported above. The question, therefore, remains an open one and is a promising problem for further experiment.

## THE PAPER

A single grade of wood pulp paper has been used throughout all of the experiments. It was of the type commonly described as "kraft," used in large quantities by a prominent cable manufacturer and furnished by a well known paper manufacturer. It was in the form of tape 2.5 cm wide and 0.1 mm thick. Its specific gravity was about 1.0 and its air resistance 640 seconds.

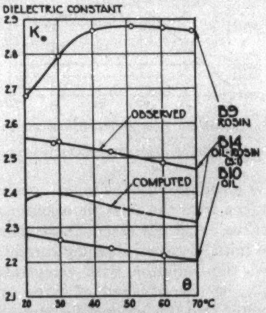

FIG. 11—VARIATION OF DIELECTRIC CONSTANT WITH TEMPERATURE

For rosin (B9), oil (B10) and their 1:3 mixture (B14)

In view of the wide variation of the electric constants of paper with the amount of residual moisture, the assembled capacitor before impregnation was dried and evacuated at 0.1 mm hg pressure and 105 deg C. By variation of the time under these conditions and by frequent conductivity measurements, all paper samples were brought to a standard value of final conductivity of approximately 1.6 x $10^{-15}$ mhos per cm. Considerable variation as among different samples in

TABLE III—COMPARISON OF PAPER SPECIMENS
Index of Dryness

| Specimen | Temp. deg C | $\lambda'$ mho/cm³ | Temp deg C | Power factor |
|---|---|---|---|---|
| A 2 | 104.7 | $1.74 \times 10^{-15}$ | 60.0 | 0.00233 |
| A 3 | 105.0 | $1.52 \times 10^{-15}$ | 60.1 | 0.00243 |
| A 7 | 105.0 | $1.92 \times 10^{-15}$ | 60.0 | 0.00237 |
| A 8 | 105.4 | $2.74 \times 10^{-15}$ | 60.4 | 0.00228 |
| A10 | 104.4 | $2.76 \times 10^{-15}$ | 61.1 | 0.00230 |
| A13 | 104.2 | $1.78 \times 10^{-15}$ | 60.9 | 0.00219 |
| A14 | 104.5 | $2.78 \times 10^{-15}$ | 60.3 | 0.00236 |
| A15 | 104.3 | $2.04 \times 10^{-15}$ | 59.0 | 0.00222 |
| A16 | 104.4 | $1.79 \times 10^{-15}$ | 58.8 | 0.00214 |
| A17 | 104.5 | $3.22 \times 10^{-15}$ | 60.1 | 0.00236 |
| Average | 104.6 | $2.23 \times 10^{-15}$ | 60.1 | 0.00230 |

the measured values of this final conductivity was encountered, as shown in Table III; but in view of the very low order of magnitude of the conductivity, the values given may be taken as indicating a fairly uniform condition of the paper as regards moisture. Moreover these values indicate that the paper was extremely dry. The approximate uniformity over the whole range of specimens is also indicated by the relatively small variation in the values of the power factor of the dry paper specimens as shown in the last column of Table III.

*Loss and Power Factor.* Paper of this type, even in the extremely dry condition, shows a pronounced dielectric absorption as may be seen from the oscillograms of charge and discharge currents shown in the earlier papers.[1] This means that under alternating stress the paper shows dielectric loss and power factor far in excess of values based on the final conductivity alone. The agreement of computed and measured losses for the paper alone have also been given in the earlier papers. In Figs. 18 to 24 the variation with temperature of the dielectric loss for the dry paper is indicated for each specimen in its relation to the loss in the oil and the subsequent loss in the impregnated specimen. The general shape of the temperature power factor curve for paper may be seen in Figs. 15 to 17.

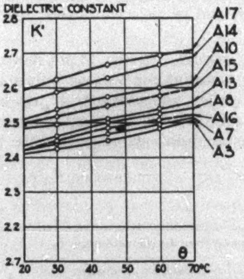

FIG. 12—DIELECTRIC CONSTANT—TEMPERATURE RELATIONS OF DRY PAPER SPECIMENS

*Dielectric Constant.* The measurements of dielectric constant of oil, of paper, and of impregnated paper have permitted the computation of the dielectric constant of wood pulp fiber and also the relative volume in which the oil combines with the paper, as follows:

$K'$ = dielectric constant of dry paper specimen. (paper + air space.)

$K''$ = dielectric constant of impregnated paper specimen. (paper + oil.)

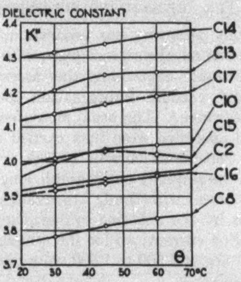

FIG. 13—DIELECTRIC CONSTANT—TEMPERATURE RELATIONS OF IMPREGNATED PAPER SPECIMENS

$K_o$ = dielectric constant of impregnating oil.

$K_p$ = dielectric constant of solid paper fiber.

$m$ = volume ratio, paper to air, and paper to oil.

$$\sigma = \text{"paper constant"} = \frac{m}{K_p}.$$

We have then the following relations for a two layer dielectric, and which are assumed to hold for the combination of paper and oil:

$$K' = \frac{(1 + m)\, K_p}{m + K_p} = \frac{1 + m}{1 + \sigma} \tag{1}$$

$$K'' = \frac{(1 + m)\, K_o K_p}{m K_o + K_p} + \frac{(1 + m)\, K_o}{1 + \sigma\, K_o} \tag{2}$$

For every set of specimens, the quantities $K'$, $K''$, and $K_o$ are all measured directly. Using the foregoing equations we may thus compute the values of $K_p$, $m$, and so $\sigma$. These values are shown in Table IV with the probable error indicated as based on the average of nine sets of values. It is seen, therefore, that for uniform winding, drying, and impregnating conditions, the quantity, $\sigma = \dfrac{m}{K_p}$ appears as a constant of the paper which is independent of the temperature. The variation with temperature of the dielectric constant $K'$ of the dry paper specimen itself is shown in Fig. 12.

TABLE IV—VARIATION WITH TEMPERATURE OF AVERAGE PAPER CONSTANTS

| | Average paper constants | | | Dielectric constant of dry paper dielectric | |
|---|---|---|---|---|---|
| Temp. deg C | Volume ratio Paper: Air Paper: Oil | Dielectric constant of solid paper fiber | Ratio: $m/K_p$ | Observed average of nine specimens | Computed from average constants |
| $\theta$ | $m$ | $K_p$ | $\sigma$ | $K'$ | $K'$ |
| 30 | 2.82 ± 0.09 | 5.45 ± 0.09 | 0.517 ± 0.014 | 2.50 ± 0.05 | 2.52 |
| 45 | 2.87 ± 0.11 | 5.55 ± 0.09 | 0.517 ± 0.020 | 2.54 ± 0.05 | 2.55 |
| 60 | 2.90 ± 0.12 | 5.60 ± 0.10 | 0.518 ± 0.024 | 2.56 ± 0.05 | 2.57 |

## THE IMPREGNATED SPECIMENS

Immediately following the separate measurements on paper and on oil, the oil was drawn into the vacuum temperature tank containing the assembled paper capacitor and vacuum impregnation took place as described elsewhere.[2] The usual measurements on the impregnated specimen were then carried out; that is, short time continuous current charge and discharge curves, with the amplifier-oscillograph, long time steady continuous current with the D'Arsonval galvanometer; power factor by the Schering bridge; and total alternating charging current; all for the temperature range 30 deg to 60 deg and 500 to 1,500 volts continuous and alternating voltages.

Impregnated paper shows the phenomenon of dielectric absorption and residual charge in marked degree. The oscillographic records of charge and discharge current, as shown in the earlier papers, readily permit the computation of the equations of the charge and discharge currents, and so the further computation of that portion of the total dielectric loss which is due to dielectric absorption. The difference between the charge and discharge curves permits computation of the conductivity and of the loss arising therein. The sum of the losses thus computed from the d-c measurements has been found throughout to be in excellent agreement with the direct measurement of the loss on the Schering bridge. An example of this agreement is shown in Table V giving a summary of the measurements and computations on the three impregnated specimens, C-15, C-16, and C-17. These three specimens were impregnated with the oils B-15, B-16, and B-17, which, it will be recalled, are basically the same, B-16 and B-17 representing two stages of deterioration by oxidation. A better picture of the influence of this deterioration on the electrical behavior of the impregnated paper will be seen in Figs. 15 to 17, and 21 to 23. The chief interest in Table V is to indicate those quantities which are measured and those which are computed, and the close agreement between the alternating loss as measured, shown in the fifth column, and the same loss as computed from the d-c measurements, as shown in the last column. The computed losses are the sum of those due to reversible absorption and to irreversible conduction.

The general nature of the influence of the properties of the paper and of the oil on the impregnated product may be studied with greatest advantage from the standpoint of the changes in dielectric constant, in power factor, and in dielectric loss as related to temperature.

*Dielectric Constant.* In Fig. 13 are shown the values of dielectric constant for various impregnated specimens as related to temperature. It will be seen that in general, the dielectric constant increases with increasing temperature, showing in this respect the

TABLE V—ANALYSIS OF POWER FACTOR AND DIELECTRIC LOSS AT 1,500 VOLTS AND 60 CYCLES BY COMPUTATION FROM D-C CHARACTERISTICS

Impregnated Paper Specimens C15, C16, C17

| | | | | | Computed from d-c characteristics | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured at 60 cycles | | | Reversible absorption | | | Irreversible conduction | | | Total | |
| Specimen | Temp. deg C | Charging current amp. $\times 10^{-6}$ | Power factor | Dielectric loss watt $\times 10^{-6}$ | In phase component of current amp. $\times 10^{-6}$ | Power factor | Dielectric loss watt $\times 10^{-6}$ | Initial constant current amp $\times 10^{-6}$ | Power factor | Dielectric loss watt $\times 10^{-6}$ | Power factor | Dielectric loss watt $\times 10^{-6}$ |
| | $\theta$ | $I''$ | $\tan \psi$ | $P$ | $I_r'$ | $\tan \psi_r$ | $P_r$ | $I_i'$ | $\tan \psi_i$ | $P_i$ | $\tan \psi_e$ | $P_e$ |
| C15 | 28.9 | 691 | 0.00318 | 3,294 | 2.168 | 0.00314 | 3,252 | 0.049 | 0.00007 | 74 | 0.00321 | 3,316 |
| | 44.4 | 695 | 0.00286 | 2,983 | 1.950 | 0.00280 | 2,925 | 0.051 | 0.00007 | 76 | 0.00287 | 3,000 |
| | 60.0 | 694 | 0.00263 | 2,735 | 1.736 | 0.00250 | 2,604 | 0.107 | 0.00015 | 160 | 0.00265 | 2,764 |
| C16 | 30.4 | 674 | 0.00315 | 3,185 | 2.100 | 0.00312 | 3,150 | 0.032 | 0.00005 | 48 | 0.00317 | 3,198 |
| | 46.0 | 677 | 0.00292 | 2,965 | 1.847 | 0.00273 | 2,770 | 0.118 | 0.00017 | 177 | 0.00290 | 2,947 |
| | 60.1 | 681 | 0.00307 | 3,136 | 1.878 | 0.00276 | 2,817 | 0.167 | 0.00025 | 250 | 0.00301 | 3,067 |
| C17 | 30.7 | 710 | 0.00394 | 4,194 | 2.597 | 0.00366 | 3,895 | 0.241 | 0.00034 | 361 | 0.00400 | 4,256 |
| | 46.2 | 714 | 0.00456 | 4,887 | 2.532 | 0.00355 | 3,800 | 0.560 | 0.00079 | 840 | 0.00434 | 4,640 |
| | 60.3 | 715 | 0.00669 | 7,164 | 3.176 | 0.00444 | 4,764 | 1.400 | 0.00196 | 2,100 | 0.00640 | 6,864 |

influence of the paper as seen in Fig. 12 rather than of the oil whose dielectric constant decreases with increasing temperature, as shown in Fig. 10. Note that in Fig. 13 the influence of the paper is also seen in the relative positions of specimens C-15, C-16, and C-17, as compared with the corresponding paper specimens. There is no obvious explanation of the slight differences as among these three paper specimens other than possible slight variations in the conditions of assembly. The values of $K''$ indicated in Fig. 13 together with the values of $K'$ given in Fig. 12 were those used for computing the values of $K_p$, the dielectric constant of solid paper fiber, and the other constants given in Table IV.

The general comparison of the curves of Figs. 12 and 13 suggests at once that variations in the dielectric constant of the impregnated samples are largely determined by the dielectric constant of the oil. It is in accord with general experience that the dielectric constant of impregnated paper may be computed from the values for the separate constituents when their relative volumes in the impregnated sample are known. From equations (**1**) and (**2**), it may be readily seen that the increase in dielectric constant, brought about by impregnation, expressed as a ratio is:

$$\frac{K''}{K'} = \frac{(1+\sigma)\,K_o}{1+\sigma\,K_o} \qquad (3)$$

or expressed as a percentage change:

$$\frac{\Delta K}{K'} = \frac{K_o - 1}{1+\sigma\,K_o} \qquad (4)$$

in which $\Delta K = K'' - K'$

In either case, it is seen that for uniform conditions of winding, drying and impregnation of a given paper, the increase in dielectric constant at a given temperature is a function of the dielectric constant of the oil $K_o$ only. Since the paper constant $\sigma$ is approximately independent of the temperature, equations (**3**) and (**4**) must therefore hold for all temperatures. In Fig. 14 the drawn curves, showing the increase of dielectric constant on impregnation as a function of $K_o$, the dielectric constant of the impregnating oil, were computed using the values of $\sigma$ given in Table IV and the equations (**3**) and (**4**) above. The measured values are indicated in the small circles. The independence to temperature of this relationship is shown by the practical coincidence of the curves for the three temperatures, 30 deg, 45 deg, and 60 deg. The excellent agreement between computed and observed values of the increase of the dielectric constant on impregnation confirms the assumption that the formulas for a two-layer dielectric apply equally to the mixture of the oil and paper. This leads to the further certainty that in well impregnated paper, practically all of the space originally occupied by air in the dry paper specimen becomes completely filled with oil after impregnation. These facts are the underlying basis of the use of measurements of capacitance as related to pressure variations during manufacture, as a measure of the degree of impregnation of high-voltage cables. If air is present in any considerable amount, as in air patches, bubbles, etc., the dielectric constant changes with pressure. On the other hand, if the paper is thoroughly impregnated no such variation is to be expected. It may be said in passing, however, that there is much evidence of a varying degree of completeness of impregnation which seems to lie below the range which may be detected by changes in dielectric constant. There is a range of condition in which residual air or moisture in amounts too small to occupy any substantial proportion of the total volume, may yet vary widely and have an important bearing on the degree of impregnation and the resulting life of the insulation under prolonged stress.

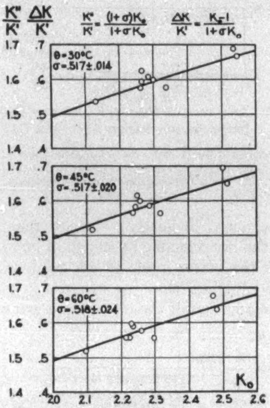

FIG. 14—INCREASE IN DIELECTRIC CONSTANT WITH IMPREGNATION AS A FUNCTION OF $K_o$, THE DIELECTRIC CONSTANT OF THE IMPREGNATING OIL

*Power Factor*. The general influence of the separate constituents, paper and oil, on the final product in the matter of power factor, is indicated in Figs. 15, 16, and 17, in which the power factor temperature relations are plotted for the three specimens, C-15, C-16, and C-17, and also in the data in Table V. In the figures the lowest curve $\psi_o$ gives the power factor temperature relation for the oil alone. The curve $\psi'$ gives the corresponding curve for the paper, and the curve $\psi''$ that for the impregnated specimen. The intermediate curve $\psi_r''$ is computed from the d-c charge and discharge curves. The difference at any one temperature between the curves $\psi'$ and $\psi_r''$ represents the increase in power factor due to reversible absorption and this difference is designated as $\Delta\psi_r$. This is the component of the increase in $\psi$, over that of the paper alone, which is due to reversible absorption. The remainder of the increase $\Delta\psi_i$ is the increase in power factor due to conduction of the oil, and which is spoken of in these papers as the irreversible conduction of the impregnated paper.

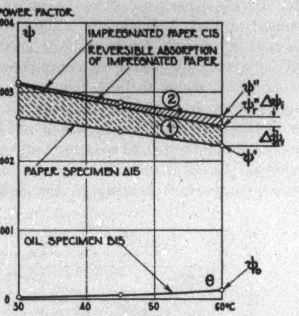

Fig. 15—Analysis of Power Factor at 1,500 Volts. Impregnated Paper Specimen C15

Increase in power factor due to impregnation:
(1) Increase in reversible absorption: $\Delta\psi_r$
(2) Contribution of irreversible conduction: $\Delta\psi_i$

It will be noted in general, that of the total power factor of the impregnated specimen, a large proportion of it with the better grade of oils used, is due to the paper; and further, that the increase in power factor due to the addition of the oil is much greater than the

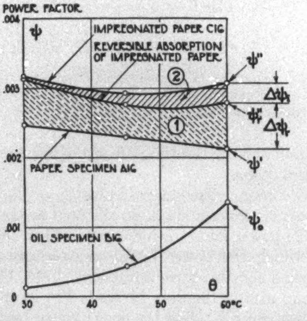

Fig. 16—Analysis of Power Factor at 1,500 Volts. Impregnated Paper Specimen C16

Increase in power factor due to impregnation:
(1) Increase in reversible absorption: $\Delta\psi_r$
(2) Contribution of irreversible conduction: $\Delta\psi_i$

sum of the values of the power factor of paper and of oil. This latter is a well known result of a combination of two dielectrics within the same capacitor and is in qualitative accordance with Maxwell's theory of dielectric absorption. With increasing conductivity of the oil as indicated in Figs. 16 and 17, the components $\Delta\psi_r$ and $\Delta\psi_i$, the increases due to reversible absorption and irreversible conduction respectively, increase substantially, so that as the conductivity and the power factor of the oil itself increase, their influence on the impregnated specimen finally becomes greater than the influence of the paper.

*Dielectric Loss.* The foregoing curves tracing the behavior of power factor before and after impregnation are plotted directly from the measurements. A more striking picture of these changes, however, is afforded by expressing the results in terms of dielectric loss. This is readily accomplished through the measurements of voltage, power factor and total charging current. In Figs. 18 to 24 are shown the relation between dielectric loss and temperature for seven of the total of ten specimens which have been studied. Each figure shows the loss in the oil $W_o$, the loss in the dry paper $W'$, and the loss in the impregnated specimen $W''$, all based on direct measurements. The curve $W_r''$ is also included giving the computed separation of the total increase of loss over that of the paper, into the two components $\Delta W_r$ and $\Delta W_i$, due to reversible absorption and irreversible conduction respectively. Fig. 18 shows the influence of the thin water white oil, B-8. This was one of the purest oils of the group, having initially very low conductivity and power factor. It is seen that in spite of the low conductivity of the oil, and the low value of $\Delta W_i$, the loss due to absorption $\Delta W_r$ (area "1") is quite large. Fig. 19 shows the influence of a well known cable oil, B-10, and Fig. 20, the effect of mixing rosin with oil B-10. As seen, the addition of the rosin causes a substantial increase in the loss $\Delta W_r$, and shifts the temperature of minimum loss to lower values. It has been seen in Fig. 13 that rosin

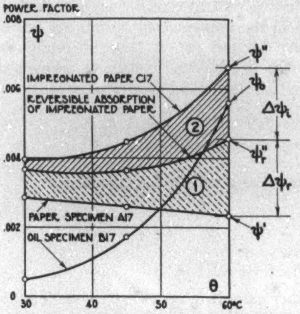

Fig. 17—Analysis of Power Factor at 1,500 Volts. Impregnated Paper Specimen C17

Increase in power factor due to impregnation:
(1) Increase in reversible absorption: $\Delta\psi_r$
(2) Contribution of irreversible conduction: $\Delta\psi_i$

has also a very pronounced influence on the dielectric constant. Figs. 21, 22, and 23 show the influence on power loss of progressive deterioration as found in specimens C-15, C-16, and C-17. Other data on these specimens have been given in connection with Table V and Figs. 15, 16, and 17. The pronounced influence of the changes in the oil is at once evident, and we discuss it further below. Fig. 24 is included because of the special interest attaching to oil B-13, the semi-refined oil of naphthene base. As will be seen, this oil has an exceptionally high conductivity, which is reflected in pronounced degree in the impregnated specimen. The values of loss and power factor shown for this oil could not be tolerated in insulation for high voltage. The oil, however, has other interesting properties, notably in the matter of stability under high stress, which are to be described in another paper.

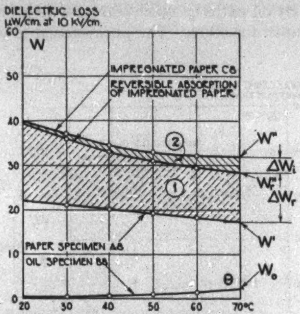

FIG. 18—ANALYSIS OF SPECIFIC DIELECTRIC LOSS AT 10 KV PER CM IMPREGNATED PAPER SPECIMEN C8

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

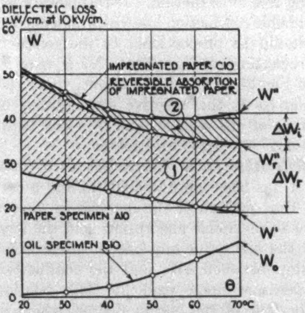

FIG. 19—ANALYSIS OF SPECIFIC DIELECTRIC LOSS AT 10 KV PER CM IMPREGNATED PAPER SPECIMEN C10

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

## DISCUSSION

The chief purpose of these studies has been to find, if possible, some definite relationship or correlation between the properties of the basic constituents, paper and oil, and those of the impregnated paper. As stated at the outset, the electrical properties of both paper and oil are highly complex, and even anomalous, and as a consequence, the application of such theories as we have for mixtures of dielectrics, is practically impossible because the usual normal constants of materials invoked in theoretical discussion, cannot be evaluated. Dry paper itself shows pronounced dielectric absorption and the oils generally show a conductivity varying with the time. What values, therefore, of dielectric constant and conductivity are to be selected for each in an effort to apply, for example, Maxwell's theory? We have made many efforts to find constants of the two materials which might be used, but in all cases, the results are roughly qualitative only, when an effort is made to predict the behavior of the impregnated material.

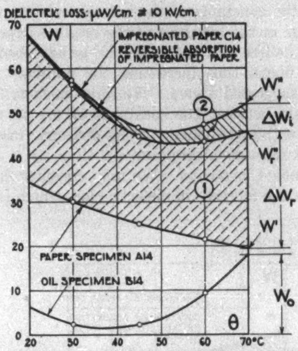

FIG. 20—ANALYSIS OF DIELECTRIC LOSS AT 10 KV PER CM. SET 14 IMPREGNATED WITH 3:1 MIXTURE OF OIL B10 AND ROSIN

Increase in dielectric loss with impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

We are forced, therefore, to seek some empirical relationship, and here the effort to trace a correlation of properties before and after impregnation has been much more successful. This correlation has been possible only through the separation of the increase of loss in the impregnated specimen into its two constituents through the oscillographic measurements of the short time charge and discharge curves.

Before impregnation, the dielectric loss in dry paper is entirely due to reversible absorption. The charge and discharge curves are almost exactly equal and opposite to each other. The loss due to irreversible conduction in dry paper is so small as to be entirely negligible as compared to that due to reversible absorption. The exact origin or cause of dielectric absorption in paper is a most interesting unsolved question. In the author's opinion, it must be associated with the surface conditions over the network of cellulose fibers, over which surfaces there must be an assemblage of ions with greater or less freedom of movement, arising in the residual moisture and air. It is not necessary to pursue this picture further than to point out that it may readily be invoked to explain the decaying charge and discharge curves, a polarization in addition to that due to the solid cellulose structure, and a very low value of final or long time conductivity as measured under continuous potential. When the oil enters the paper it is obvious that these surface conditions will be changed and that there must be some relationship between the constants of the impregnating liquid and the change in the behavior of the original paper. For example the free ions in the oil may be adsorbed by the cellulose fibers, thus increasing the numbers already there as suggested above. We have in fact, found a relationship between the constants of the oil and the increase in the component of the dielectric loss which is due to reversible absorption.

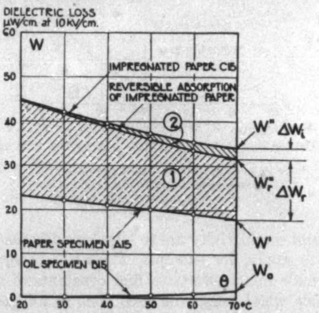

FIG. 21—ANALYSIS OF SPECIFIC DIELECTRIC LOSS AT 10 KV PER CM IMPREGNATED PAPER SPECIMEN C15

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

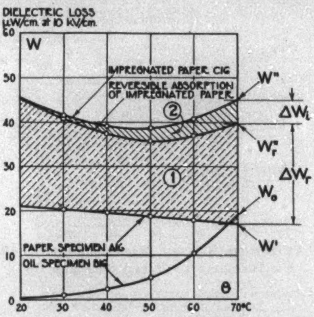

FIG. 22—ANALYSIS OF SPECIFIC DIELECTRIC LOSS AT 10 KV PER CM IMPREGNATED PAPER SPECIMEN C16

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

*Irreversible Conduction.* We may consider first that portion of the increase in dielectric loss which is due to irreversible conduction. The difference between the charge and discharge curves of any composite dielectric usually has a constant value commonly attributed to the normal conductivity of the material. Impregnated paper behaves in this manner. The impregnation of the paper introduces the element of irreversible conduction as shown in the various curves above in the upper areas "2". In view of the negligible value of this component in the dry unimpregnated paper, it is evident that the presence of irreversible conduction in the impregnated paper must be due to the oil. This component is, therefore, a pure conduction phenomenon and may be thought of as a straight leakage through the impregnated specimen; in other words, the leakage afforded by oil paths in which there are no barriers due to the paper structure. The phenomenon is probably not actually so simple; however, the effect is due to an average total ionic movement in many separate paths permitting free ionic motion. If this picture is correct, the irreversible conduction loss which appears on impregnation should be proportional to the conductivity of the impregnating oil $\lambda_o$. That this is true is clearly shown in Fig. 25 in which the quantity $\Delta W_i$ is plotted in relation to $\lambda_o$ the effective conductivity over the whole range of oils studied, and over the temperature range 30 deg—60 deg C for each oil.

*Reversible Absorption: Correlation with Conductivity of Oil.* It has been more difficult to find a correlation between that portion of the increase in dielectric loss $\Delta W_r$, due to reversible absorption, and the basic properties of the oils. For any one oil there is a definite relationship between $\Delta W_r$ and the conductivity over the temperature range studied. This relationship is shown for four of the oils in Fig. 26 which indicates that the quantity $\Delta W_r$ for any one oil when plotted against the conductivity of the oil forms a smooth curve. For the high conductivity oils C-13 and C-17, the relationship is approximately linear. For oils of moderate conductivity, C-7 and C-10 $\Delta W_r$ is practically independent of the oil conductivity $\lambda_o$ over a wide temperature range. The points pertaining to the lower conductivity oils C-8 and C-15 have not been plotted in order to avoid confusion. These points all lie close to the ascending portion of the curve for C-10. For all the specimens as the oil conductivity $\lambda_o$ is carried to low values as for example, through the lowering of temperature, it is seen that $\Delta W_r$ increases. This is a well known property due to reversible absorption and is in quantitative accord with the Maxwell-Wagner theory of dielectric absorption. It is also seen in Fig. 26 that the points on the different curves corresponding to any particular value of temperature themselves lie on a smooth curve. The explanation of this fact is not entirely obvious. However, it may be noted that the purer the oil and the lower its conductivity, the lower the value of $\lambda_o$ at which the curves turn upward. This relationship will have the tendency to throw the values of $\Delta W_r$ for the different oils at say 30 deg on a smooth curve. The fact that the values for any higher temperature also fall on a smooth curve then becomes only an indication that the law of increase of conductivity with temperature is the same for all the oils.

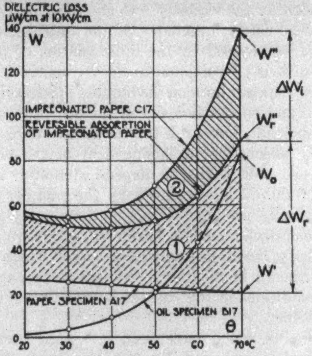

Fig. 23—Analysis of Specific Dielectric Loss at 10 Kv per Cm Impregnated Paper Specimen C17

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

*Reversible Absorption: Correlation with Ionic Density of Oil.* We have sought, however, for a wider correlation between the properties of the impregnated product and the properties of the impregnating oil. Since one type of paper is used and in an approximately uniform condition throughout, it would appear that it should be possible to tie in the electrical behavior of the impregnated product in all cases with some single property or constant of the respective oils. It is obvious from the results described in the foregoing paragraph that the conductivity of the oil will not serve for this purpose, each oil showing a different curve. We have, therefore, looked to the properties of surface tension and viscosity as these obviously have a direct bearing on the degree of penetration of the oil into the paper. The values of these quantities alone did not appear to lead to any promising correlation. However, it was immediately found that the product of the viscosity $\eta$ and effective conductivity $\lambda_o$ led to an interesting uniform relationship. As indicated in the earlier part of the paper this product is a measure of the number of free ions present in the oil and therefore, may be taken as an index of the "electrical purity" of the oil. In Fig. 27 we have plotted the relationship between the increases in power factor $\Delta\psi_r$ and dielectric loss $\Delta W_r$ due to reversible absorption, in their relation to the product $\eta\lambda_o$ for all of the oils studied, in their original condition. For the low conductivity oils, the points plotted are the average values for the temperatures 30 deg, 40 deg, 50 deg and 60 deg, the points lying very close together. For the higher conductivity oils, the plotted points correspond to different temperatures. It will be seen that there is a remarkable relationship between the increase of loss due to the reversible absorption and the product of the viscosity and conductivity among all oils in the normally pure and undeteriorated condition. Plotting points for a variety of oils and at different temperatures results in a smooth curve.

A similar relationship exists over the extreme range of conductivity afforded by the three oils B-15, B-16, and B-17, which it will be recalled are all the same oil, the first stage undeteriorated and two other stages of increased deterioration due to oxidation. This gives three basic differences in conductivity at 30 deg in the relationship 1 to 5 to 20, with a further extension of range of the product $\eta\lambda_o$ through temperature variation. Fig. 28 shows the curves between $\Delta W_r$, $\Delta\psi_r$, and $\eta\lambda_o$ for these three oils. It is seen that they are closely similar in shape and in position to those in Fig. 27. In the upper range, however, the curves of Fig. 28 fall

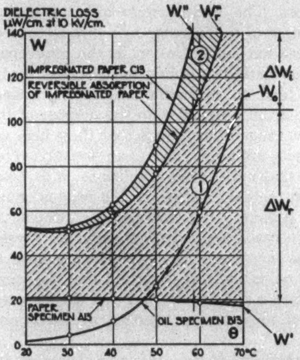

Fig. 24—Analysis of Specific Dielectric Loss at 10 Kv per Cm Impregnated Paper Specimen C13

Increase in dielectric loss due to impregnation:
(1) Increase in reversible absorption: $\Delta W_r$
(2) Contribution of irreversible conduction: $\Delta W_i$

slightly below those of Fig. 27 and so the results for the two groups of oils have been plotted separately.

The curves of Figs. 27 and 28 are of the general type

$$y = a + bx + cx^2 \tag{5}$$

If we attempt to interpret this relationship in terms of the Maxwell theory of absorption, we find the constant term accounted for by the fact that even if the impregnating oil had zero conductivity, there would still be a loss in the combination of oil and paper due to reversible absorption. The linear term $bx$ indicates that there is a component of the increase $\Delta W_r$ directly proportional to the free ion concentration in the impregnated oil. As the conductivity reaches higher values we find this increase, due to reversible absorption, rising more rapidly than in proportion to the number of free ions. An obvious suggestion here is that these high values of conductivity are usually due to an elevation of temperature and that under these conditions, it is possible to picture an actual increase in the original number of free ions present. It is furthermore evident that this type of increase would be less rapid for those oils in which the increase of conductivity has been brought about by oxidation. It is certain that the ions in this case are larger and heavier and that the increase in the number of ions due to temperature elevation would be less.

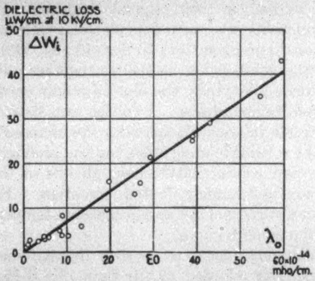

FIG. 25—DIELECTRIC LOSS DUE TO IRREVERSIBLE CONDUCTION ($\Delta W_i$) AS A FUNCTION OF THE CONDUCTIVITY ($\lambda_o$) OF IMPREGNATING OILS

Our knowledge of the origins or causes of dielectric absorption in dry paper, and the data at present available, do not seem to warrant any extensive effort at any explanation of the relationship between the properties of the oil and those of the impregnated paper which has been shown above. In the foregoing the behavior of dry paper under continuous potential has been attributed to the adsorption by the surfaces of the cellulose fibers of electrolytic ions arising in residual air and moisture. This picture assumes a limited movement of such ions under electric stress and a resulting contribution to the total polarization of the structure. If it can be assumed that on impregnation the free ions which are present in the oil join, through the processes of adsorption, those ions which have already been taken up by the surfaces of the paper structure before impregnation, we have at least a tentative picture which is in accord with the facts. That is, the increase in loss due to irreversible absorption would be proportional to the number of new ions added and we may assume that the motion of adsorbed ions on the surface of the cellulose fibers is different from the motion of ions in the body of the liquid, and so might well be independent of the viscosity. In any event, the following may be safely asserted. Of the total increase in dielectric loss caused by the impregnation of paper a portion of it is proportional to the conductivity of the oil, and so depends both on the number of ions originally in the oil and on the viscosity of the oil. Another and more important portion of the increased loss is due to reversible absorption, is independent of the viscosity of the oil, and seems to depend definitely on the purity of the oil as measured by the number of free ions originally present. While no certain explanation of this relationship can yet be offered, such explanation undoubtedly lies in the particular way in which the oil replaces the air in the finer interstices of the paper and in the conditions in the contact layer between oil and cellulose fiber.

The results which have been presented pertain to one type of paper only. For this reason no effort has been made to evaluate the constants of equation (5) nor to propose a general formula for the predetermination of the losses and behavior of impregnated paper in general. It would however, be a simple matter to write such a formula for the particular paper here studied. It is obvious that the most promising direction for further knowledge of the interesting relationships here brought out would be a continuation of similar studies with the paper as the variable. If such a study could be carried out, it might be possible to evaluate the constants $a$, $b$, and $c$, in formula (5) in terms of the properties of the paper, and so to write down formulas permitting the predetermination of the electrical con-

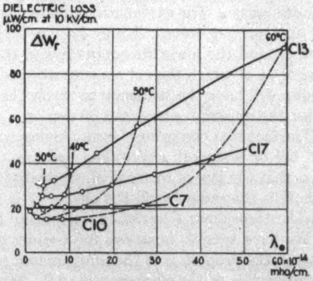

FIG. 26—INCREASE IN DIELECTRIC LOSS ($\Delta W_r$) DUE TO REVERSIBLE ABSORPTION AS A FUNCTION OF THE CONDUCTIVITY OF THE IMPREGNATING OILS ($\lambda_o$)

stants of any paper as impregnated with any oil; in other words, to place the design of impregnated paper insulation on an accurate engineering basis. Unfortunately, the continuation of this work under past conditions is no longer possible. It is hoped, however, that it may be resumed in the not too distant future.

### ACKNOWLEDGMENT

The active prosecution of this work has only been possible through the encouragement, confidence, and financial support of the Utilities Research Commission of Illinois, to whom grateful acknowledgment on behalf of the Johns Hopkins University and of the author of this paper is hereby extended.

Cordial acknowledgment is also made of the enthusiastic and skillful cooperation, in the experiments and in the analysis and preparation of the results, of Mr. A. Baños, Jr., and Dr. S. K. Waldorf. Thanks are also extended to Professor W. B. Kouwenhoven and to other members of the laboratory staff who from time to time have extended helpful cooperation.

### CONCLUSIONS

1. The electrical and other physical properties of 10 insulating oils have been examined. A single grade of paper was impregnated with each of the oils. The electrical properties of the impregnated paper have been studied as related to the original characteristics of the oils.

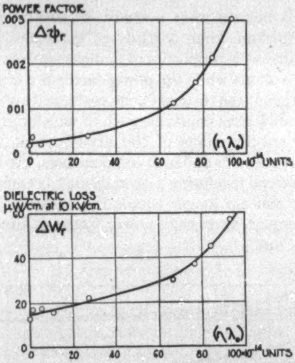

Fig. 27—Increase in Power Factor ($\Delta\psi_r$) and Dielectric Loss ($\Delta W_r$) as a Function of the Product ($\eta\lambda_o$) Specimens Impregnated with Undeteriorated Oils

2. The measurements of dielectric constant permit determination of the relative volume content of oil and of paper fiber in the impregnated specimen, as well as the basic dielectric constant of the fiber itself.

3. The dielectric constant of an insulating oil is increased by oxidation without corresponding changes in density.

4. The dielectric loss in impregnated paper consists of two components, one due to conduction and the other due to dielectric absorption. A general relation exists for all the oils and over the temperature range studied, between each of these components of loss and common physical properties of the impregnating oil.

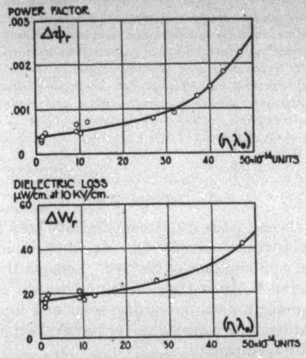

Fig. 28—Increase in Power Factor ($\Delta\psi_r$) and Dielectric Loss ($\Delta W_r$) Due to Reversible Absorption as a Function of the Product ($\eta\lambda_o$), Showing the Effect of Three Stages of Deterioration of Oil B15

5. The conduction loss in impregnated paper is directly proportional to the effective conductivity of the oil regardless of type.

6. The increase on impregnation, of the loss due to reversible absorption, is a definite function of the product of the viscosity and the conductivity of the impregnating oil, regardless of type.

7. The product of viscosity and conductivity is a measure of the free ion content of the oil. It is proposed as a measure of electrical purity of an impregnating oil. The function connecting this quantity with the increase in loss has been determined for one paper. Its determination for other papers should make it possible to write a general expression for the predetermination of the total loss resulting from the impregnation of any type of paper with any type of oil, in terms of the separate properties of each.

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## Discussion

For discussion of this paper see page 689.

# Capacitance and Loss Variations with Frequency
## And Temperature in Composite Insulation

BY HUBERT H. RACE*
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***Synopsis.***—*Variations in electrical properties of composite insulation with changes in temperature and frequency are important because they lead to concepts of physical causes of such variations and, therefore, indicate how to obtain improved electrical properties in commercial materials. Typical experimental data are presented showing the capacitance and loss characteristics of synthetic resin laminated materials and of imperfect composite dielectrics made from combinations of fused quartz or glass and semi-conducting liquids. An example is given showing agreement between calculated and observed characteristics of such a glass-liquid combination.*

*Theoretical analyses are given, showing that the general form of the capacitance and loss characteristics could be caused by any one of several physical mechanisms.*

*As a result of these studies it seems probable that in synthetic resin laminated products semi-conducting materials in small insulated pockets or fibers can account for observed characteristics and can be represented mathematically by the Maxwell-Wagner theory. It is also shown that capacitance and loss measurements at one frequency and temperature cannot generally be used to predict corresponding values under different conditions.*

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### A. INTRODUCTION

FOR several years measurements have been made on a wide variety of materials, including liquids, solids and combinations of the two. Some of the results on liquid dielectrics have been published,[1] and this paper[2] presents data on certain solid and liquid-solid combinations with suggestions for physical explanations of the observed results.

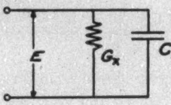

FIG. 1—PARALLEL CIRCUIT EQUIVALENT TO SAMPLE

Kirch[3] in a recent series of articles also emphasizes the extreme importance to design engineers of such studies because of the need for clarifying physical explanations of observed phenomena. A knowledge of the causes and mechanisms responsible for either desirable or undesirable properties will indicate how the first may be obtained and the second eliminated or at least reduced.

### B. ELECTRICAL CHARACTERISTICS OF EXPERIMENTAL MOLDED MATERIALS

It has been found convenient to interpret all measurements in terms of the equivalent parallel circuit shown in Fig. 1. The complex expression for the reciprocal impedance of the measuring circuit is given by the relation

$$Z^{-1} = G_x + i\omega C_x = \omega C_v(\epsilon'' + i\epsilon') \qquad (1)$$

in which

$G_x$ = the equivalent parallel conductance of the sample
$C_x$ = the equivalent parallel capacitance of the sample
$\omega = 2\pi f$, where $f$ = electrical frequency in cycles per second
$i = \sqrt{-1}$
$C_v$ = capacitance of the same geometric arrangement of electrodes in vacuum

For comparative purposes it is convenient to study unit quantities which may be defined by comparing the two forms of equation (1) as follows:[4]

$$\epsilon' = C_x/C_v = \text{dielectric constant} \qquad (2)$$

$$\epsilon'' = G_x/\omega C_v = \text{loss factor} \qquad (3)$$

$$\sin \tan^{-1} \epsilon''/\epsilon' = \text{power factor} \qquad (4)$$

If $\epsilon'$ is not constant a study of variations in $\epsilon''$ is more important than a study of variations in power factor, since $\epsilon''$ is proportional to dielectric loss per cycle per unit volume while the power factor is a trigonometric function of the ratio between coefficients of dielectric loss and dielectric constant, each of which may vary as independent functions of the experimental variables. At low frequencies and high temperatures, the loss angle in commercial insulating materials may become large so that the sine no longer equals the tangent, and $\epsilon''$ is much more accurate than power factor as a measure of dielectric loss.

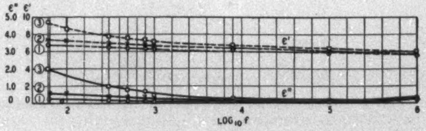

FIG. 2—SPECIAL SAMPLE, PHENOLIC RESIN WITH MICA, BAKED

(1) 30 deg C, (2) 60 deg C, (3) 90 deg C

Typical data[5,6] for experimental phenolic resin compounds having differing ingredients and amounts of cure are shown in Figs. 2 and 3. For the better material, both capacitance and loss are practically independent of frequency at room temperature, but at 90 deg C both show an appreciable increase at low frequencies. This characteristic is greatly accentuated in the uncured

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1. For references see end of paper.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

material, in fact the results plotted in Fig. 3 are extremely interesting because they indicate the causes for similar characteristics found on a much smaller scale in the better sample. Data from Fig. 3 for several frequencies are given in Table I as an excellent illustration of the large variations in characteristics observed in poor materials and the advantages of $\epsilon''$ over power factor as a true measure of dielectric loss.

TABLE I—CAPACITANCE AND LOSS DATA FOR PARTIALLY CURED TEXTOLITE

| Frequency cps | $\epsilon'$ | | | $\epsilon''$ | | | P.F. | | |
|---|---|---|---|---|---|---|---|---|---|
| | 60 | $10^3$ | $10^6$ | 60 | $10^3$ | $10^6$ | 60 | $10^3$ | $10^6$ |
| Temp. °C 30 | 12.2 | 10.2 | 7.4 | 2.0 | 0.8 | 0.5 | 0.162 | 0.078 | 0.067 |
| 60 | 19.6 | 11.8 | 7.9 | 9.5 | 2.3 | 0.6 | 0.437 | 0.191 | 0.076 |
| 90 | 45.3 | 16.4 | 8.4 | 30.0 | 7.0 | 0.6 | 0.552 | 0.393 | 0.071 |

The first conclusion from these data is that *loss and capacitance measurements taken at one frequency and temperature can not be used to predict the characteristics at other frequencies and temperatures except under special conditions where the type of variation to be expected is already known.*

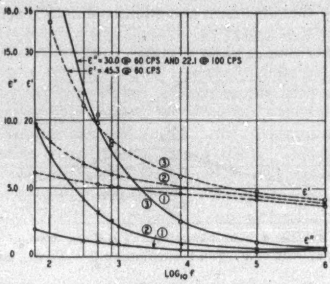

FIG. 3—SPECIAL SAMPLE, PHENOLIC RESIN WITH MICA AND CARBON BLACK, UNBAKED

(1) 30 deg C, (2) 60 deg C, (3) 90 deg C

The second conclusion is that *when $\epsilon'$ is not constant, or the loss angle is large, changes in power factor are not accurate measures of changes in dielectric loss.*

This is especially true at 60 cycles per second; for example, in Table I the loss per cycle per unit volume ($\epsilon''$) increased 15 fold as the temperature increased from 30 to 90 deg C, but the power factor increased less than four fold because the effective capacitance also increased nearly four fold. This has been recognized and the effect has been accounted for by calculating a loss factor by multiplying power factor by dielectric constant[7] but the definition of $\epsilon''$ given by equation (3) seems much more logical and meaningful. The third conclusion is that the physical causes of such large changes are worthy of considerable further study. The following calculations and experiments resulted.

## C. THEORETICAL STUDY

The curves in Fig. 3 appear to be portions of the general curves for an imperfect dielectric having relaxation characteristics: *i. e.,* portions to the right of the frequency for maximum loss in Fig. 4. There are at least three physical mechanisms each of which can give such characteristics. It is conceivable that in the same composite dielectric all three may be important under different frequency and temperature conditions and even that two or all of them might be operative to different degrees under the same conditions.

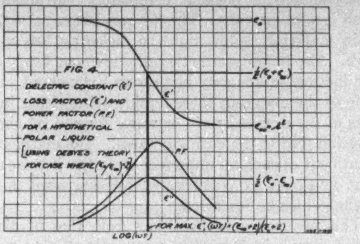

FIG. 4

The three mechanisms are:

A. Orientation of polar particles in a viscous medium.

B. Translation of charged particles, either for relatively long distances, as at low frequencies in a liquid, or for relatively short distances, as at high frequencies in a liquid, or along semi-conducting surfaces of fibrous material, or within semi-conducting cells of a solid.

C. Formation of polarized films or space charges at the electrodes.

Mechanism A seems highly improbable as an explanation of the data in Fig. 3 nevertheless curves showing the general form of the results of this theory[8] are given in Fig. 4.

The equations for the dielectric constant and loss factor of a polar liquid from which these curves were plotted were given in an earlier paper,[1] and it is of particular interest to note the simple relations which hold at the frequency $f_m$ at which the maximum occurs.

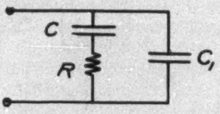

FIG. 5—ONE FORM OF EQUIVALENT CIRCUIT FOR MECHANISM B

Anderson[9] measured capacitance and loss for several solids at high frequencies but was unable to obtain any correlation with Debye's theory.

Such a correlation is not to be expected since the simple theory applies only to dilute solutions. It seems however that the variations found by Anderson are similar to those we have found and can be explained by the Maxwell-Wagner theory, as indicated below.

Mechanism B seems highly probable as an explanation of the data shown in Fig. 3. This is simply stating in a slightly different way the mechanism described by K. W. Wagner[10] in his extension of Maxwell's theory of a layer dielectric. For this particular discussion instead of thinking of a layer dielectric, we visualize minute semi-conducting pockets completely surrounded by good insulating walls. The d-c conduction of synthetic resin materials is low but the dielectric loss may be high. Also before synthetic resins are completely cured, conducting liquids may be present throughout the volume of the material, these liquids being either ingredients of the uncured resin or water formed by chemical reaction during the curing process. The mathematical treatment of such an imperfect dielectric is the same as that developed by Wagner and the behavior is the same as that which he described.

This physical concept differs from that of Murphy and Lowry,[11] in that they assume insulating micelles having semi-conducting surfaces while we picture semi-conducting pockets completely surrounded by insulating walls. Their picture may be true for fibrous materials containing adsorbed moisture while ours may be true for molded or varnish-treated materials. In either case the mathematical equivalent should be the same.

Neglecting d-c conduction caused by continuous current paths from one electrode to the other through an imperfect dielectric, the heterogeneous series and parallel, conductance and capacitance paths can be represented by the equivalent electrical circuit shown in Fig. 5. The reciprocal impedance of this circuit can be expressed as

$$Z^{-1} = \frac{R\omega^2C^2}{1 + R^2\omega^2C^2} + i\left[\frac{\omega(C + C_1) + R^2\omega^3C^2C_1}{1 + R^2\omega^2C^2}\right] \quad (5)$$

Comparing this relation with equation (1) we find the following expressions for the effective dielectric constant $\epsilon'$, loss factor $\epsilon''$ and power factor of such an imperfect dielectric.

$$\epsilon' = \frac{1}{C_v}\left[C_1 + \frac{C}{1 + R^2\omega^2C^2}\right] = \frac{\alpha^2\epsilon_0 + \omega^2\epsilon_\infty}{\alpha^2 + \omega^2} \quad (6)$$

$$\epsilon'' = \frac{1}{\omega C_v}\left[\frac{R\omega^2C^2}{1 + R^2\omega^2C^2}\right] = \frac{\alpha\omega(\epsilon_0 - \epsilon_\infty)}{\alpha^2 + \omega^2} \quad (7)$$

$$PF = \sin\tan^{-1}(\epsilon''/\epsilon') \quad (8)$$

where

$\alpha = 1/RC$ = time constant of circuit

$\epsilon_0 = (C_1 + C)/C_v$ = effective dielectric constant at zero frequency

$\epsilon_\infty = C_1/C_v$ = effective dielectric constant at infinite frequency

$\omega = 2\pi f$

$f$ = frequency in cycles per second

The variations of these coefficients with frequency is shown in Fig. 6 for the case where $C = C_1$.

By taking the first derivative of equation (7) with respect to $\omega$, it may be shown that for the frequency $f_m$ at which maximum loss occurs the following relations hold.

$$\omega_m = \alpha \quad (9)$$

or

$$f_m = 1/2\pi RC = \alpha/2\pi \quad (9a)$$

$$\epsilon_m' = \frac{1}{2}(\epsilon_0 + \epsilon_\infty) = \frac{1}{2}\left[\frac{2C_1 + C}{C_v}\right] \quad (10)$$

$$\epsilon''_m = \frac{1}{2}(\epsilon_0 - \epsilon_\infty) = \frac{1}{2}\left(\frac{C}{C_v}\right) \quad (11)$$

These equations are identical to corresponding relations[2] obtained for Debye's theory of polar molecules.

All that this correlation means is that both theories are built upon the assumption of an exponential relaxation function whose time constant is $\alpha$. Both theories lead to variations of capacitance and loss with $\log_{10}f$ of exactly the same form and additional data is necessary to determine which (if either) of these physical pictures is applicable in any given case.

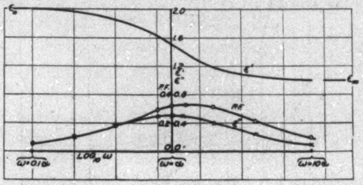

FIG. 6—DIELECTRIC CONSTANT ($\epsilon'$), LOSS FACTOR ($\epsilon''$) AND POWER FACTOR (P.F.) FOR CASE WHERE $C = C_1$ IN CIRCUIT OF FIG. 5

Contrary to the statement of Gemant,[12] we find that these two effects need not occur in widely separated frequency ranges but might occur in the same range under certain conditions. Therefore *the frequency at which the maximum loss occurs cannot be used alone as a criterion of the physical mechanism which is responsible for observed variations.*

If there is an air film between the surface of the material and the test electrodes, or if one or more layers of loss-free insulation is placed in series with the test piece, then the equivalent circuit shown in Fig. 7 may be nearer a true representation of the composite dielectric than that of Fig. 5. It can be shown[13] that these two circuits are exactly equivalent if the relations given by equations (24-32) in the appendix exist between their coefficients. Therefore such a composite insulation will also show the general characteristics of Fig. 6.

Mechanism C which can be represented by Fig. 7, also offers a possible explanation of the observed data since it is known that even with the best possible contact between the surfaces of a solid dielectric and the electrodes, polarization may occur. If a constant unidirectional potential is applied for sufficient time this back potential may become approximately equal and opposite to the applied potential.[14]

Sinjelnikoff and Walther[15] state that all the a-c losses may be accounted for by measuring the true resistance of a dielectric, taking into account this polarization potential. This, again, seems to be simply another way of looking at the Maxwell-Wagner theory.

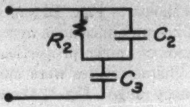

FIG. 7—SECOND FORM OF EQUIVALENT CIRCUIT FOR MECHANISM B

Whitehead[16] has shown that oil alone and oil impregnated paper both show relaxation characteristics. He studies their alternating current behavior by using a modification of Von Schweidler's[17] theory in which the relaxation function is assumed to be a sum of several exponential terms instead of a power function which was used by Von Schweidler. Assuming one term only of the exponential function, Dr. Whitehead shows curves of capacitance and loss changes with frequency exactly similar[18] to those given in Figs. 4 and 6. This again is to be expected since all three mathematical treatments start with the assumption of an exponential relaxation function. For the more general case where the relaxation function is not a simple exponential this direct correspondence no longer holds.

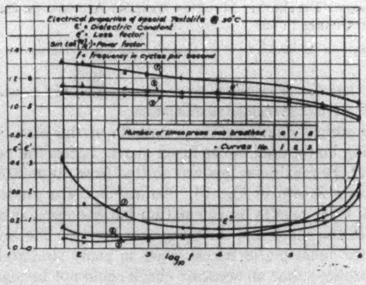

FIG. 8—CAPACITANCE AND LOSS MEASUREMENTS FOR A SPECIAL TEXTOLITE AT 30 DEG C

From the above analysis of these three mechanisms which lead to qualitatively similar results it seems that these additional conclusions may be drawn.

*a. Any mechanism causing an exponential current-time discharge curve after the removal of a constant potential, should also cause an a-c dielectric loss-frequency curve having a maximum at* $f_m = \alpha/2\pi$.

*b. Inversely, if a maximum is observed in the a-c loss-frequency curve, the exponent of the current-time curve of the same material should be given by this same relation.*

*c. Conversely, if in a given range of frequency or relaxation time, one of these effects is not found, the other should also be absent.*

## D. EXPERIMENTAL VERIFICATION OF MECHANISM B

Two types of results will now be shown which seem to verify the concept that conducting liquids (water, solvents, etc.) in small pockets throughout the volume of synthetic molded materials are responsible for the observed electrical behavior.

In Figs. 8-11 are shown the results of a series of tests to determine the effects of changing the conditions of gas evolution during the process of curing flat sheets of paper base textolite. These sheets are molded between flat steel platens and if the sheet is pressed and cooled under continuous pressure all gaseous products must either escape through the edges of the sheet by diffusion or be trapped in pockets throughout the volume of the sheet. Upon cooling, water or other vapors recondense, giving the semi-conducting pockets. Now if the press is opened several times, or allowed to "breathe" as it is called, during the curing of the sheet, it should be much easier for these vapors to escape. Therefore several samples from the same molding stock were pressed under identical pressure, temperature and time conditions, the only difference being in the number of times the press was opened or "breathed" during the curing of the sheet. In each case the sheet was cooled in the mold under pressure.

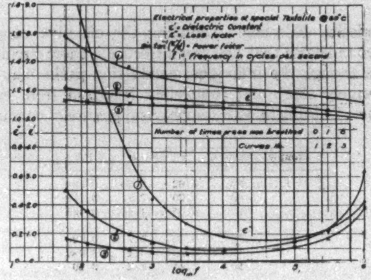

FIG. 9—CAPACITANCE AND LOSS MEASUREMENTS FOR A SPECIAL TEXTOLITE AT 60 DEG C

The capacitance and loss characteristics were then measured at three temperatures with very interesting results. In the first place, the first two conclusions drawn from the data in Table I were again verified. From the table shown in Fig. 11 taking sample No. 1 for example, the loss per unit volume increased ten fold as the temperature was increased from 30 to 90 deg C, but the power factor only increased about five fold because the effective dielectric constant had about doubled in this range.

The increase in effective capacitance with increased temperature is thought to be caused by increased conductivity and effective short circuiting of portions of the composite dielectric. Doubling the effective capacitance indicates that half the dielectric is short circuited even though the individual conducting paths may be extremely short and completely insulated from each other. This fits in with the physical picture of conducting liquids having a negative resistance-temperature coefficient in insulating cells.

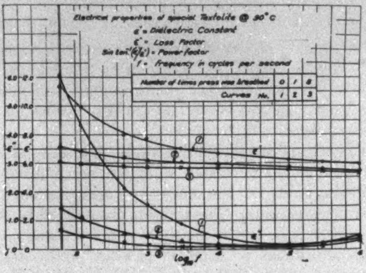

Fig. 10—Capacitance and Loss Measurements for a Special Textolite at 90 Deg C

| Sample | Temp° C | $\epsilon''$ | $\epsilon'$ | P.F. |
|---|---|---|---|---|
| 1 | 30 | 0.62 | 6.55 | 0.094 |
|  | 60 | 2.25 | 7.9 | 0.274 |
|  | 90 | 6.05 | 11.4 | 0.468 |
| 2 | 30 | 0.15 | 5.7 | 0.026 |
|  | 60 | 0.50 | 6.1 | 0.082 |
|  | 90 | 1.45 | 7.2 | 0.20 |
| 3 | 30 | 0.07 | 5.45 | 0.013 |
|  | 60 | 0.17 | 5.66 | 0.03 |
|  | 90 | 0.70 | 6.10 | 0.098 |

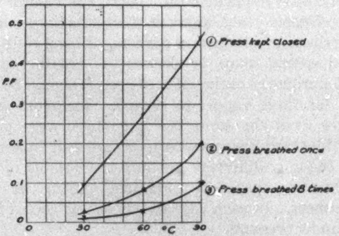

Fig. 11—60-Cycle Power Factor of Special Textolite

Showing the effect of allowing gases to escape during curing

Secondly, *these data prove that conducting liquids are a major factor in the cause of high effective capacitance and high dielectric loss in molded materials.*

Thirdly, *the data indicate that in molded materials conducting liquids are held within small pockets, or if they are absorbed on the surface of the paper fibers according to the physical picture of Murphy and Lowry,*[11] *these conducting paths must be insulated from each other.*

That the former would give quantitatively similar results we have attempted to show by building artificial imperfect dielectrics from known components. The first attempt is shown in Figs. 12 and 13. Small fused quartz tubes of known dimensions were filled with semi-conducting liquids of known properties and the capacitance and loss characteristics were measured over the available frequency range. Fig. 12 shows that the maximum in the loss curve may occur at very low frequencies and that wherever both the $\epsilon'$ and $\epsilon''$ curves are rising with decreasing frequency, some form of relaxation is probably responsible. These curves are strikingly similar to those shown in Figs. 2, 3, 8, 9 and 10 and indicate that *the Maxwell-Wagner theory probably accounts for all the data presented in this paper.*

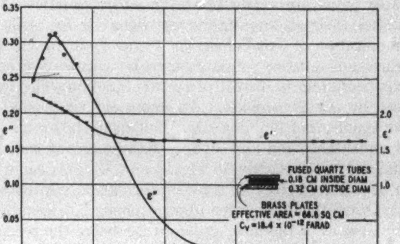

Fig. 12—Capacitance and Loss Measurements for an Imperfect Dielectric Made by Sealing Alcohol in Small Fused Quartz Tubes

Constants for the alcohol are $\epsilon' = 4.62$ and $\rho = 1.7 \times 10^{10}$ ohms per cm cube

By simply changing the constants of the semi-conducting liquid used in the fused quartz tubes, the position of the maximum loss was shifted from 30 to 20,000 cps, as is shown in Fig. 13. An attempt was made to check these results by calculation but the circular section of the tubes and the air spaces between the tubes and the brass plates necessitated so many simplifying assumptions that an accurate check could not be made.

Therefore the same two liquids were used in a double-walled glass cell of better geometric design and the measurements repeated as shown in Figs. 14 and 15. Here again the same characteristic functions were obtained and with the simpler geometric design they can be checked very closely by calculation. For example, let us determine the critical values for Fig. 15. The dimensions of the cell are shown. The characteristics of the semi-conducting liquid are shown in Fig. 16. The dielectric constant measurements of this liquid were very uniform but the measurements of equivalent parallel conductance were quite difficult especially at radio frequencies because of high losses. However the results could best be interpreted as a constant value of conductance independent of frequency, as is shown on the curve sheet.

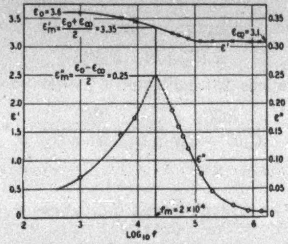

FIG. 13—CAPACITANCE AND LOSS MEASUREMENTS FOR AN IMPERFECT DIELECTRIC MADE BY SEALING AN ALCOHOL IN SMALL FUSED QUARTZ TUBES

Constants for the alcohol are $\epsilon' = 16.0$, $\rho = 7.02 \times 10^6$ ohms per cm cube

From the dimensions of the cell we calculate

$$C_v = 0.0884 \times 10^{-12}\,\frac{219.8}{0.4} = 48.6 \times 10^{-12} \text{ farad} \quad (12)$$

$$C_{empty\ cell} = 0.0884 \times 10^{-12}\,\frac{219.8}{\frac{0.2}{1}+\frac{0.2}{5}}$$

$$= 81 \times 10^{-12} \text{ farad} \qquad (13)$$

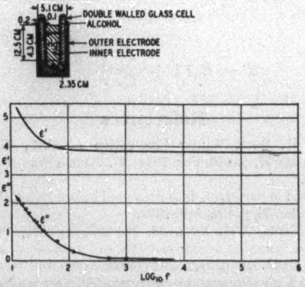

FIG. 14—CAPACITANCE AND LOSS MEASUREMENTS FOR AN IMPERFECT DIELECTRIC MADE BY SEALING AN ALCOHOL IN A DOUBLE WALLED GLASS CELL

Constants for the alcohol are $\epsilon' = 4.62$, $\rho = 1.7 \times 10^{10}$ ohms per cm cube

in which the dielectric constant for the glass is assumed to be 5. The actual measured capacitance of the empty cell was found to be $80 \times 10^{-12}$ farads, so the calculated effective area was corrected to 217 instead of 219.8 sq cm.

Now the equivalent circuit for this combination is represented by Fig. 7, since the glass is assumed to be loss free and the liquid has both conductance and capacitance. Therefore we have

$$C_3 = 0.0884 \times 10^{-12}\left[\frac{5 \times 217}{0.2}\right] = 480 \times 10^{-12} \text{ farad} \quad (14)$$

$$C_2 = 0.0884 \times 10^{-12}\left[\frac{16 \times 217}{0.2}\right]$$

$$= 1{,}530 \times 10^{-12} \text{ farad} \qquad (15)$$

$$R_2 = 7.02 \times 10^6\left(\frac{0.2}{217}\right) = 6.47 \times 10^3 \text{ ohms} \qquad (16)$$

Now converting these to equivalent coefficients in Fig. 5 by using equations (**30-32**) we have

$$C = 114.5 \times 10^{-12} \text{ farad} \qquad (17)$$

$$C_1 = 366 \times 10^{-12} \text{ farad} \qquad (18)$$

$$R = 11.3 \times 10^4 \text{ ohms} \qquad (19)$$

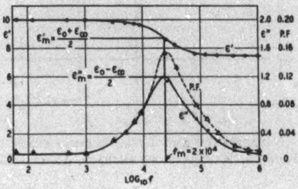

FIG. 15—CAPACITANCE AND LOSS MEASUREMENTS FOR AN IMPERFECT DIELECTRIC MADE BY SEALING AN ALCOHOL IN A DOUBLE WALLED GLASS CELL

Constants for the alcohol are $\epsilon' = 16.0$, $\rho = 7.02 \times 10^6$ ohms per cm cube

Then from equations (**9**), (**10**) and (**11**) the characteristic coefficients for this composite dielectric may be determined. These calculated values are tabulated below for comparison with the experimentally determined data.

TABLE II—COMPARISON BETWEEN CALCULATED AND OBSERVED VALUES FOR FIG. 15

| | $f_m$ | $\epsilon_0$ | $\epsilon_\infty$ | $\epsilon_m''$ |
|---|---|---|---|---|
| Calculated | $1.23 \times 10^4$ | 9.89 | 7.53 | 1.18 |
| Observed | $2.0 \times 10^4$ | 10.0 | 7.4 | 1.2 |

*The close agreement proves the applicability of the theory in determining capacitance and loss characteristics of such a composite dielectric.*

The author is happy to acknowledge his indebtedness to his coworkers, particularly S. I. Reynolds of the General Engineering Laboratory, for assistance in making the measurements reported in this paper.

## E. CONCLUSIONS

1. In composite dielectrics, capacitance and loss measurements taken at one frequency and temperature

cannot be used to predict characteristics at other frequencies and temperatures except under special conditions where the type of variation to be expected is already known.

2. When $\epsilon'$ is not constant, or the loss angle is large, changes in power factor are not accurate measures of changes in dielectric loss but changes in $\epsilon''$ truly represent such changes measured as watts loss per cycle per unit volume per (unit potential gradient)$^2$.

3. The frequency $f_m$ at which maximum loss occurs cannot be used alone as a criterion of the physical mechanism which is responsible for observed variations since under certain conditions the different mechanisms may possibly cause changes in characteristics in the same frequency range.

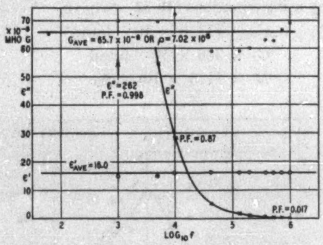

FIG. 16—CAPACITANCE AND LOSS MEASUREMENTS FOR THE ALCOHOL REFERRED TO IN FIGS. 13 AND 15

4. Some form of the Maxwell-Wagner theory of imperfect dielectrics is the most probable explanation of data on molded materials presented in this paper.

## Appendix

### RELATIONS BETWEEN COEFFICIENTS TO MAKE IDENTICAL THE CIRCUITS SHOWN IN FIGS. 5 AND 7

For a simple circuit composed of $R_p$ and $C_p$ in parallel, the complex expression for the admittance is

$$Y = \frac{1}{R_p} + iwC_p = \frac{1 + pR_pC_p}{R_p} \qquad (20)$$

Also for the simple circuit composed of $R_s$ and $C_s$ in series we have the impedance.

$$Z = R_s + \frac{1}{iwC_s} = \frac{1 + pR_sC_s}{pC_s} \qquad (21)$$

In the second form of each of these expressions the operator $(p)$ has been substituted for $(iw)$.

In a similar way the circuits shown in Figs. 5 and 7 are represented by equations (22) and (23) respectively.

$$Y = \frac{1}{\dfrac{1}{pC_3} + \dfrac{R_2}{1 + pR_2C_2}} = \frac{pC_3 + p^2R_2C_2C_3}{1 + pR_2(C_2 + C_3)} \qquad (22)$$

$$Y = pC_1 + \frac{pC}{1 + pRC} = \frac{p(C + C_1) + p^2RCC_1}{1 + pRC} \qquad (23)$$

By the operational calculus, the condition under which these last two equations are identical is that corresponding coefficients of $(p)$ must be equal. Therefore we have:

$$C_3 = C + C_1 \qquad (24)$$

$$R_2C_2C_3 = RCC_1 \qquad (25)$$

and

$$R_2(C_2 + C_3) = RC \qquad (26)$$

From equations (25) and (26):

$$R_2 = \frac{RCC_1}{C_2(C + C_1)} = \frac{RC}{C_2 + (C + C_1)} \qquad (27)$$

from which

$$C_2 = \frac{C_1}{C}(C + C_1) \qquad (28)$$

and substituting back in equation (26) we have

$$R_2 = R\left(\frac{C}{C + C_1}\right)^2 \qquad (29)$$

Equations (24), (28) and (29) give the coefficients of Fig. 7 in terms of those of Fig. 5 to make the two circuits electrically equivalent.

Again, if the coefficients of Fig. 7 are known, those which will make Fig. 5 electrically equivalent may also be derived from the above equations and are as follows:

$$C = \frac{C_3^2}{C_2 + C_3} \qquad (30)$$

$$C_1 = \frac{C_2C_3}{C_2 + C_3} \qquad (31)$$

$$R = R_2\left(1 + \frac{C_2}{C_3}\right)^2 \qquad (32)$$

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4. See ELEC. ENGG. **51**, p. 354 (1932).

5. The high temperature measurements were made possible by the use of conducting paint electrodes using thick paste of colloidal graphite in a suitable mixture of G.E. No. 1550 nitrocellulose lacquer and G. E. No. 1501 thinner.

6. A complete description of equipment used in making these measurements is being prepared by W. A. Ford and S. I. Reynolds for publication in the *G. E. Review*.

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18. See Discussion, A.I.E.E. TRANS. **51**, p. 402, June 1932.

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# Discussion

## THE DIELECTRIC LOSSES IN IMPREGNATED PAPER

(WHITEHEAD)

## CAPACITANCE AND LOSS VARIATIONS WITH FREQUENCY AND TEMPERATURE IN COMPOSITE INSULATION

(RACE)

**A. A. Bolsterli:** Of the many valuable results of Doctor Whitehead's new series of researches I wish to single out those given under the heading *Dielectric Constant.* This subject, no less than the others dealt with in the paper, is of great interest not only to the cable engineer, but to the designer of static condensers as well.

Considering the far from simple structure of paper as a conglomeration of fibers, it is remarkable that the system paper-air or paper-oil should resolve itself, as far as dielectric constant is concerned, into a simple two-layer dielectric. Evidently the author starts with this assumption using it for the determination of $(K_p)$ and $(m)$. The correctness of the values of $(K_p)$ and $(m)$ as determined from test data rests therefore upon the degree to which the aforementioned assumption holds true. While there is no question in my mind that the author's assumption is very well founded, it would be interesting to know whether any other checks were made to verify it. I have in mind the determination of $(m)$ from mechanical data. If $(S)$ is the specific gravity of the dry paper, $(S_p)$ that of the solid paper fiber, the volume ratio paper: air is given by:

$$m = \frac{S}{S_p - S} \tag{1}$$

*The International Critical Tables* (Vol. II, p. 237) give the specific gravities of fibers determined in benzene after Vignon as follows:

| | |
|---|---|
| Cotton | 1.50 to 1.55 |
| Linen | 1.50 |
| Hemp | 1.48 |
| Jute | 1.48 |

No value is given for cellulose fibers prepared from wood which make up Kraft paper. Taking the author's values of $S = 1$ and $m = 2.82$ (Table IV, for 30 deg C) and applying the aforementioned formula (1), the specific gravity of paper fiber is found to be $S_p = 1.354$, which value differs appreciably from the above figures for related fibers. Probably the difference can be ascribed, at least in part, to moisture content, the author's figures referring to highly dried paper, whereas nothing is known as to the condition of the fibers to which the other figures refer.

If a test specimen is built up in the shape of a plane-layer condenser with a number of sheets of paper as the dielectric, it is possible to vary the volume ratio paper-air or paper-oil, that is to say the author's $(m)$, by compressing the condenser in a hydraulic press. If $(n)$ denotes, the percentage compression, *i.e.*, the reduction in layer thickness referred to the thickness uncompressed, of the layer, the volume ratio $(m)$ for dry paper at compression $(n)$ is:

$$m = \frac{S}{S_p(1-n) - S} \tag{2}$$

where $(S)$ is the specific gravity of the layer uncompressed and $(S_p)$ that of the solid paper fiber assumed to be incompressible. Substituting the values obtained by (2) in the author's formula (1), the dielectric constant can be calculated for any degree of compression. Since the corresponding capacity measurements of the condenser furnish the measured dielectric constant, an accurate check of the two-layer hypothesis would seem to be possible by this method, which by way of extension is applicable to impregnated paper as well.

Fig. 1 of this discussion shows the data obtained on a test condenser made up of 200 layers of 5 sheets each of 0.75-mil Kraft paper. For the calculated curve the values $K_p = 5.45$ and $S_p = 1.354$ from the author's paper were used. In spite of the fact that these values are in all probability only approximately true for the paper we used, the agreement between calculated and measured values is fair, as is seen from the curves.

Mechanical compression, while scarcely a factor in cable design, is a well known means of controlling dielectric constant in paper condensers, whether they are of the compressed-gas dry type or the impregnated type. The method indicated above would seem to afford an extension of Doctor Whitehead's method of predetermining the dielectric constant to include the feature of compression.

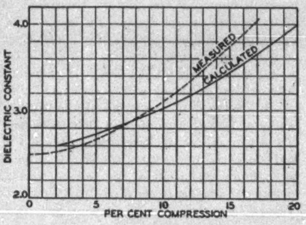

FIG. 1—DIELECTRIC CONSTANT OF DRY PAPER DIELECTRIC IN FUNCTION OF MECHANICAL COMPRESSION

Dielectric layer consisting of 5 sheets of ¾ mil condenser tissue (calendered Kraft) thoroughly dried, under heat and vacuum before test. For the measured values, compression is referred to thickness under 50 lb per sq in. compression

**W. A. Del Mar:** The research work done by the cable manufacturers necessarily is directed toward immediate commercial ends. Hence, while a vast amount of information is unearthed in the manufacturers' laboratories, in the course of solving practical problems, there is little opportunity to organize it into presentable form, once the practical problems are out of the way.

In these papers which record researches under the auspices of the various groups interested in cable engineering, the manufacturer's engineer encounters a great deal of familiar material and is pleased to see it organized into a form where it is a permanent record. Doctor Whitehead has gone through the experience of seeing a simple problem expand and unfold into seemingly endless new problems, with no end in sight. It is, therefore, a cause of genuine regret that we find Doctor Whitehead stating that this work must cease for lack of financial support.

Cable manufacturers have discovered that oil suppliers are particularly ignorant of the properties of their oils as related to their performance in cables. Transformer manufacturers found that it required considerable effort on their part to interest oil refiners in sludge prevention, but several of them are now active in that field. No such activity exists with regard to cable oils. It would be greatly to the advantage of the oil refiners if they would take advantage of Doctor Whitehead's fine ability, experience, organization and equipment, to educate them about their cable oils and enable them to sell their product intelligently to the cable manufacturers.

Doctors Whitehead and Race appear to differ somewhat in their views of the bearing of their respective experimental data on the Maxwell theory of absorption in composite dielectrics. It would be interesting to have the two authors explain the reasons for their views in greater detail.

**Hubert H. Race:** Referring to the sentence in which Doctor Whitehead states that "In particular, in the case of insulating oils and cellulose paper, each of these materials is so complex in its dielectric properties that, to the experimenter, it is almost immediately obvious that a quantitative agreement with any theory of dielectric loss cannot be expected from the studies of the behavior of the paper when impregnated with the oil," it seems that this comment may be made. Such a statement should not be discouraging to the investigator but rather it should challenge him to try to determine the physical reasons underlying these complexities. The characteristics of a dielectric are anomalous only so long as they remain unexplained and it seems that the greatest value to be gained from insulation research will come from increased understanding of the causes of such characteristics.

Naming experimentally determined characteristics, of which dielectric absorption is a good example, is of little value unless they can then be studied sufficiently to obtain a physical understanding of their causes. For example, if it can be shown that the losses in oil impregnated paper are definitely dependent upon current conduction in minute restricted paths within cellulose fibers or in absorbed conducting films along the surfaces of cellulose fibers then such measurements can serve as definite guide posts in changing the factory treatment of paper and oil so as to decrease these conduction losses. Or again, if it can be shown that conduction plays only a minor part and that adhesive or polar orientation forces in cellulose-oil-water interfaces are mainly responsible for the observed phenomena, then an entirely different line of attack will be necessary in order to reduce these losses. Some data presented at the November meeting of the National Research Council in Baltimore (see p. 53 of the report of the Committee on Electrical Insulation of the Div. of Engg. and Industrial Research of the N.R.C., Dec. 1932) may be taken as a slight indication of the second mechanism as a possible factor contributing to the dielectric loss of oil impregnated paper.

Recalling a few steps in vacuum tube development will indicate the point of this comment. Little progress was made so long as "current leakage" was known only as an unexplained, externally measured property of incandescent lamps. The development of the many forms of vacuum tubes now in use was made possible only because the physical mechanisms and governing laws of phenomena such as electron emission and space charge formation were minutely studied and thoroughly understood. Correspondingly, intensive studies of the properties of dielectrics may lead to important improvements in insulating materials.

In discussing changes in dielectric constant of oil with oxidation, Doctor Whitehead stresses the non-uniform distribution of charged particles as the possible cause but neglects to mention polar orientation. In *Physics*, May 1932, W. N. Stoops of the Westinghouse Elec. and Mfg. Co. published a paper showing increases in dielectric constant with oxidation of commercial oils, which he interprets as resulting from increases in polar constituents. In the *Journal of Physical Chemistry*, July 1932, I published a paper showing that increases in high frequency losses are caused by polar particles because the hydrophil content increased with oxidation in direct proportion to the dielectric losses. I also found that a portion of the loss remained even when the hydrophil content was extrapolated to zero indicating that two mechanisms, namely the orientation of polar particles and the migration of charged particles may simultaneously be contributing toward the capacitance and loss characteristics of an insulating liquid.

In my present paper it is shown that several different mechanisms may lead to similar electrical characteristics and I should like to add that work on high loss materials such as synthetic resins may be directly applicable to oil impregnated paper even though the resultant losses in the latter are of a much smaller order of magnitude. Considerable additional work should certainly be done to obtain more information on the mechanism of dielectric loss and associated phenomena in composite insulation since losses generate heat and most failures which do not result from mechanical trouble are probably pyroelectric.

**J. B. Whitehead:** Doctor Race gives us some interesting data on a class of insulating materials which are not often discussed, namely those having very high values of dielectric loss. We note values of power factor up to 40 and 50 per cent which thus approach the values frequently observed in electromagnetic machinery.

Doctor Race has pointed out the value of the "loss factor" rather than the "power factor" for describing insulation of this class. He makes out a very good case. On the other hand, I doubt whether it would be advantageous to employ the loss factor for the high grade insulation which is necessary for high voltage equipment, as for example, impregnated paper cables. In this class, the loss per cu-cm often is so small that the values of the loss factor would become decimals of small magnitude, involving the use of negative exponents of 10. Moreover, capacitance changes with both frequency and temperature are small in this class of insulation, and there is no difficulty in passing immediately from values of power factor or phase difference to those of loss. It seems to me, therefore, that there would be no advantage in using the loss factor in discussions of insulation of this class.

The paper also presents examples of the now well known maxima of power factor with corresponding capacitance changes for complex insulation over sufficiently wide ranges of either frequency or temperature. This type of variation has been recognized by students of dielectric theory ever since the first extension of Maxwell's theory of the layer dielectric to the alternating case. Emphasis has recently been given to a similar type of variation involved in Debye's theory of polar molecular orientation. The fact that each of these phenomena has associated with it a dielectric relaxation function, also is well known. Doctor Race emphasizes again this convenient criterion for the presence of the types of loss and capacitance variations under discussion.

To the several physical pictures which Doctor Race is suggesting for aiding our thought of these matters, I would suggest that he might add that of the motion of ions of various sizes in the liquid portions of his dielectrics. As to his conclusion No. 3, that molecular orientation and dielectric absorption may occur in the same frequency range, the vital question here is whether molecules will oscillate and relatively large ions vibrate in the same frequency range of alternating stress. My own feeling is that they are not likely to do so and that changes in capacitance and power factor in commercial materials and in the lower ranges of frequency are due to the various manifestations of anomalous conduction and dielectric absorption, rather than to molecular orientation.

**R. J. Wiseman:** Doctor Whitehead's paper is an addition to several papers by him on the dielectric losses in impregnated paper which try to show us where these losses come from, some of the influencing factors and what kind or kinds of oil are best suited to obtain the highest efficiency in cable operation. This last paper tends to indicate that the so-called oil-filled type of cable is, in the last analysis, the only true one. Theoretically, this is true. Practically and economically it is not necessarily so. We have had and still have very good operation on the solid type of cable up to and including 66 kv. One must not be led to assume that by using special highly refined oils, we are going to eliminate cable failures.

Doctor Whitehead refers to power factor of the dielectric in high voltage cables and in impregnated paper condensers within the range of 0.001 to 0.003. I have yet to see either in oil-filled cable or solid type cable, a power factor of 0.001. We do get about 0.003 in the beginning, but with time, this will increase. We cannot assume, even though we would like to, that it will stay around 0.003. It is true, as Doctor Whitehead states, that under most conditions, the losses in the dielectric for all voltages are small, as compared with those in the conductor and so do not seriously limit the current carrying capacity of the cable.

We prefer not to lead the user to believe that they are not going to change nor do we want him to think they are going to increase to a dangerous value. Actually, today, the types of oils that are used are practically quite stable and the user need have no fear of them. The problem confronting the cable user today is not so much the stability of the dielectric, but the lead sheath. For the past ten years we have been urged to improve our oil and paper, lower moisture content, lower void volume, which means in turn, higher oil content. All these were necessary and have been accomplished, but we still get cable failures. An analysis of these failures indicates many due to the lead sheath. We assign the cause as defective lead and we give the manufacturer of the cable a black mark.

About two and one-half years ago the company the writer is associated with started studies on the influencing factors of good cable operation. Elaborate researches have been conducted by simulating operating conditions with overvoltage tests. As a part of this study we watched the change in power factor, hot spot temperatures, internal pressures and sheath expansion. We have had cases of practically no change in power factor up to the time of failure and again a rapidly increasing power factor, but a long time to failure; we have noted hot spots at which failure has occurred and a few cases away from a hot spot; internal pressures at the conductor have been as high as 115 lb per sq. in. and at the sheath 80 to 85 lb per sq in.; permanent expansion of the sheath and again moderate elasticity. Examination of the cable after failure has indicated migration of the oil from the conductor to the sheath, leaving dry zones in which ionization has and yet has not occurred. The most startling of all were the very high internal pressures developed. We immediately associated these with the lead sheaths and studied what influence they would have. Samples of lead sheath were subjected to constant internal pressures of 40 lb per sq in. at room temperature, 40 deg C and 53 deg C. The sheaths at 53 deg C expanded quite rapidly and burst, those at 40 deg C also showed a definite expansion and with time, burst; those at room temperature expanded, but did not burst.

Calculation of the hoop stresses in the lead showed a tensile strength over that permissible, according to recent studies such as those by Professor Moore of the University of Illinois, for the lead to stand if it is not to stretch. Here is a clue to the failure of cable and where we have assigned the cause of failure to manufacture, actually, it is an operating cause resulting from internal pressures which the lead physically cannot withstand. In improving our dielectric we have forgotten the protecting sheath. We have not changed our tables of lead sheath thicknesses ever since they were originally gotten up, which was on a rule of thumb basis. Only recently has it become serious and our next step in improved quality of cable and, therefore, cable operation, is to face the facts and increase our lead walls, particularly for cables over 2.5 in. in diameter. A 1/64 in. increase will greatly help, but we should go further and base the thickness for these large diameter cables on a maximum hoop stress of about 180 lb per sq in. for a constant internal pressure of 20 lb per sq in. Unless we do, we are not going to reduce materially the record of cable failures. The increase in cost of cable is moderate, far less than the cost of replacement of a section which has failed. This subject equally is as important to all of us as further improvement in the dielectric.

**J. B. Whitehead:** The importance of fundamental physical and chemical research into the properties of dielectrics cannot be emphasized too often.

Doctor Race has criticized more than once my use of the term "dielectric absorption" for describing the well known phenomenon of residual charge in complex dielectrics. Whether or not we understand completely all of the phenomena leading to residual charge, there obviously is a practical advantage in having a brief term for the convenient description of the phenomenon. Moreover, the use of such a brief term should not, and probably never does, imply indifference to the importance of the study of underlying causes. But beyond this, there are other even better grounds warranting the use of the term. It has been used by distinguished students of dielectrics, reaching back to the time of Maxwell, for the description of the important phenomenon of residual charge, and for which he has given us his classical theory. Let it be remembered that when two dielectrics having different values of conductivity and dielectric constant, are mixed, we shall have the phenomenon of residual charge or dielectric absorption. It may be that the conductivities and dielectric constants are complex as caused by ionic adsorption, space charge, molecular orientation, or other cause. The basis phenomenon will always remain. Perhaps Doctor Race will suggest a better term for convenient reference to this by far the most important cause of dielectric loss at low frequencies.

Doctor Wiseman raises the question as to the relation of our results to the performance of commercial cables. While the improvement of the latter is always the ultimate object of our work, I take it that the first principle of all basic research is the uncovering of new knowledge and facts. Thus, the point of view in our research has been a determinatoin of the ultimate available properties of impregnated paper, the explanation of these properties, and the laws which govern them. It may be that at the present moment, our results only constitute a remote target which it may be impossible to hit, or even reach, from the standpoint of present commercial economics and practise. On the other hand, the visibility of the target will be a stimulus for the development of new means of reaching it, and a proof of the value of additional expenditures to that end. In short, the value of spending more money to get better cables.

We have in this work however, approached very closely the conditions of practise in the oil-filled cable. I believe that our results may be used with great reliability in any comparative study of the relative values of different oils for that type of cable. Doctor Wiseman admits this, but calls attention to limitations of a quite different sort, which are inherent in the solid type of cable. Our work has not attacked the great problems of sheath expansion, and gaseous ionization as a result of temperature cycles, in the solid cable. It may be pointed out here, however, that when under progressive development, the oil-filled principle becomes more general and when, if ever, the solid cable, through increasing sheath thickness or by other means, ever reaches the stage where it is free from internal voids, engineers will then turn to the basic researches of ourselves and others who are endeavoring to formulate the underlying properties and laws of the materials, as the only limitations to performance in practise.

**H. H. Race.** Professor Whitehead has apparently misinterpreted my comment regarding the use of the term "dielectric absorption." The report on "Proposed American Standard Definitions of Electrical Terms" defines dielectric absorption "that property of an imperfect dielectric whereby there is an accumulation of electric charges within the body of the material when it is placed in an electric field." This then is an externally measured property of a composite dielectric as a whole and carries with it no necessary explanation of the physical causes of its origin. I do not object to the use of the term dielectric absorption nor have I any other name to offer, but I should like to emphasize again the need for studying more intensively the underlying physical phenomena so that for representative dielectrics answers may be obtained to questions such as the following:

1. What is the source and size of ions?
2. How far and how fast do they move?
3. Do they accumulate to form space charges at the electrodes or is the displacement uniform throughout the material?
4. How can the formation of ions be prevented?
5. What part is played by orientation of polar molecules in a viscous liquid medium?
6. What part is played by films of polar liquids adsorbed on cellulose fibers in oil impregnated paper?

# A New Method for Initiating the Cathode Of An Arc

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Associate, A.I.E.E.

## I. INTRODUCTION

THE specific form of electrical discharge in gases which we know as the electric arc is a most essential and useful element in many types of engineering apparatus and in many applications. Its utility in arc lamps, arc rectifiers, arc welders, lightning arresters spark gaps is obvious. Where the arc is useful, it owes its utility to its ability to carry large currents at a low voltage to a degree incomparably greater than that of other forms of discharge such as glows, Townsend discharges, cathode rays, positive ion currents, etc.

The origin or seat of this great capacity to carry large current at low voltage which is enjoyed by the arc resides quite definitely at the cathode, where with a drop of only ten or twenty volts, thousands of amperes per cm$^2$ are carried. In fact it is only at the cathode that the arc differs essentially from the glow for which the cathode drop is usually several hundred volts, and the current density even at atmospheric pressure is only about ten amperes per cm.[2] The problem of the formation of an arc, as distinguished from other types of discharges, then reduces to a study of the cathode of an arc, and the circumstances which cause an arc cathode rather than a glow cathode to form.

## II. THEORIES OF CATHODE OF AN ARC

Since gases are normally insulating, the maintaining of a discharge requires the presence of ionizing agents. In the gas itself, ionization by collision with molecules of electrons accelerated by the electric field, seems to be adequate to account for the observed conductivities, at least at low gas pressures. At high gas pressures, of the order of atmospheric, thermal ionization of the gas seems to play a part,[1] and it has been found that high enough temperatures are observed[2] to produce thermal ionization.

At the cathode a space charge sheath exists and the whole current must be carried either by electrons liberated from the cathode or by positive ions from the gas. If the current density is very small, the latter alternative is sufficient and is probably the mechanism of the Townsend or dark discharge occurring at high gradients, just below the sparking potential for the electrode configuration in the gas. The ionization of the gas near the cathode is produced principally by ionization by collision with gas molecules or positive ions.

As the current density in the Townsend discharge is increased, the space charge of positive ions near the cathode causes an increase in the gradient there, and finally electrons are set free from the cathode by impact of positive ions or excited atoms. The essential character of the discharge is not changed, however, and the setting free of electrons from the cathode by such impacts may well be included in the general term ionization by collision. If there is no other source of ionization than ionization by collision as thus generalized, increase in current density will change the Townsend discharge continuously into the glow with a minimum drop at the cathode of several hundred volts, and with a current density, at this minimum, of about ten amperes per cm$^2$ at atmospheric pressure, and varying as the square of the pressure. Increasing the current density above this figure raises the cathode drop.

Ionization by collision alone then can account only for low current density discharges requiring at least hundreds of volts. For an arc cathode to occur, some new ionizing agent must make its appearance. The search for what this new ionizing agent may be forms an interesting chapter in electrophysics.

The first theory was that thermionic emission at the cathode is this new ionizing agent.[3] In most types of arcs the cathode is at a high temperature, and for some arcs, certainly at a temperature high enough for sufficient thermionic emission. However, it is certain that steady arcs do exist with cathodes which are too cold for thermionic emission,[4] and that arcs are formed from glows in times which are too short for the cathode to heat up.[5] Other ionizing agents are necessary for these non-thermionic arcs. Note, however, that for these thermionic arcs a considerable energy input is necessary to bring the cathode up to the necessary temperature so that such an arc cannot be formed from a glow in a short time.

Another theory, and one which is widely accepted, is that in the arc, a very high positive ion space charge density adjacent to the cathode produces so intense an electric field there that electrons in sufficient number are pulled out from the cathode.[6] To form so intense a space charge, however, calls for a current density of several thousand amperes per sq cm[7] so that according to this theory such current densities are necessary before an arc cathode can be formed.

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

[1] Compton, K. T., *Phys. Rev.*, **21**, 266, 1923.

[2] Ornstein, *Phys. Zeits.*, **32**, 517, 1931. V. Engel and Steenbeck, *Wis. Veröff. and Siemens Konzern*, **10** (No. 2), 155, 1931.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

[3] Thomson, "Conduction of Electricity Through Gases," 2 ed., p. 604.

[4] Stolt, *Zeitz f. Phys.*, **26**, 95, 1924; *Ann d. Physik* **74**, 80, 1924.

[5] Slepian, *Jour. Frank. Inst.*, **201**, 79, 1926.

[6] Langmuir, *G. E. Rev.*, **26**, 731, 1923.

[7] Slepian and Haverstick, *Phys. Rev.* **33**, 52, 1929.

Still another theory is that very intense thermal ionization in the gas layer immediately adjacent to the cathode supplies sufficient positive ions to carry the current to the cathode.[8] Here again, because of the large heat loss from this hot gas layer to the cold cathode, a considerable current density is necessary.

We see that according to all these theories a considerable energy input density or current density at the cathode is a prerequisite for the formation of an arc cathode.

## III. METHODS FOR INITIATION OF AN ARC CATHODE

The problem with which the authors have been concerned, and whose solution forms the subject of this paper was the frequent repeated initiation of an arc cathode upon a cold electrode within a very short and precisely placed time interval, less than a thousandth of a second, and in gases at low pressures. It is well to consider the known methods of arc cathode initiation to see how closely they come to meeting the requirements of this problem.

*1. The Thermionic Cathode.* The method of using a cathode with a separate source of energy to bring it up to a temperature sufficient for thermionic emission is regularly used in hot "filament" gas-filled tubes. However, if the "filament" is to be of reasonable size, and the separate source of energy not excessively large, the filament cannot be brought up to the necessary temperature in the required small time.

*2. Separating Contacts.* When metallic contacts are separated in circuits carrying an ampere or more, an arc is formed at once. Several theories have been advanced as to the way in which the arc cathode is formed there. These theories depend upon the great concentration of the current and intensification of the electric field at the last contact point of the separating electrodes.[9,10]

Although this method is widely used in switches, arc lamps, welders, and for starting of mercury arc rectifiers, the mechanical inertia of the separating contacts makes this method impractical for solving the problem set by the authors.

*3. The Blowing Fuse.* Closely related to the method of separating contacts is the blowing of a fuse wire.

By using a fine wire or film, the quick and accurate starting of the arc can be accomplished. The requirement of quick and frequent repetition of the starting operation, however, introduces difficulties. One possibility is the quick formation and re-formation of a conducting film upon an insulating surface by condensation from a metal vapor, and the authors have had some success in this way, but the method which is described later in this paper is believed to be better.

*4. Spontaneous Transition from Glow to Arc.* A glow between electrodes may be readily and quickly started by the application of sufficient voltage. In many circumstances the glow cathode will change spontaneously into an arc cathode. For example, if the energy density at the cathode is large enough, the cathode will heat up, and may reach a temperature for sufficient thermionic emission to permit the change to an arc cathode. But at low gas pressures, since the glow current density is very low, such heating cannot occur, and at high gas pressures, the heating is still too slow to solve the problem of the rapid and repeated initiation of the arc cathode required by the authors.

Nevertheless, sudden and rapid transitions to the arc form of cathode do occur in actual glows even at low gas pressures. The causes of such transitions are not well understood, and the prevention of such occurrences is the fundamental problem of mercury arc rectifiers and similar devices.

Researches of the authors[11] and others[12] indicate that these causes are spontaneous and randomly occurring agents lasting individually for only some few millionths of a second, and which somehow cause a sufficiently high current density to appear at some point of the cathode for maintaining an arc cathode. The average frequency of occurrence of such causes varies in a direct manner with the current density and voltage of the glow. At low gas pressures, where the glow current density is very small, the average frequency of occurrence of these causes is too small for the solution of the authors' problem to be found in this way. Only at high pressures, about atmospheric, is the frequency of occurrence of these causes great enough to give certainty that an arc cathode will form within a few thousandths of a second.[5]

*5. The Electric Spark.* This method deserves a special place because it deals with a transient form of glow cathode which is particularly effective in initiating an arc cathode at high gas pressures. The spark is initiated by high voltage breakdown between spaced electrodes, and since the only ionizing agent at the cathode is ionization by collision, we must describe the cathode condition as a glow. The characterizing feature of the spark is the very rapid growth of the current sent through the discharge. Since the glow cathode which initially covers only a small area spreads rather slowly,[13] a very high current density may be built up momentarily in the glow cathode. If a sufficiently high current density may be reached in the glow the frequency of occurrence of spontaneous transition causes becomes sufficiently great to insure the prompt initiation of an arc cathode.

At low gas pressures, even with high applied voltages from sources capable of giving a rapid rate of increase of current, the current density in the glow cathode remains low and an arc is not struck. Generally, one would say that a "spark" does not form at low gas pressures.

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[8] Slepian, *Phys. Rev.*, **27**, 407, 1926.

[9] Killian, *Phys. Rev.*, **37**, 1678, 1931.

[10] Slepian, A.I.E.E. JOURNAL, **45**, 930, Oct. 1926.

[11] Slepian and Ludwig, TRANS. A.I.E.E., **51**, 92, March 1932.

[12] J. V. Issendorf, M. Schenkel, R. Seeliger, *Wiss. Veröf. d. Siemens Konz.*, IX, I, 73, 1930.

[13] Steenbeck, *Arch. f. Elek.*, **26**, 306, 1932.

*6. The High Frequency Discharge.* This method is closely related to the methods described in *4* and *5*. A discharge is started between spaced electrodes by application of sufficient voltage of high frequency. Again, since the only ionizing agent is ionization by collision, condition at the momentary cathode must be described as a glow. However, in the high-frequency glow the current density may be very large compared to that at the cathode of a steady or low-frequency glow. In the steady glow the current density at the cathode is limited by the space charge of the positive ions. But in the high-frequency glow such space charges do not have time to form. Thus high-density positive ion currents will flow in alternate half cycles and with such high current density the frequency of occurrence of spontaneous glow to arc transitions will be very great.

The method of the high-frequency discharge appears to be practical according to the experience of the authors, but they believe the new method to be described in this paper is better.

*7. Striking a New Cathode from an Already Existing Arc.* Conditions at an electrode made negative to an existing discharge are essentially the same as those at the cathode of a self-maintaining glow, except that the positive ion currents may be drawn at a voltage in itself too low for the maintenance of a glow. To insure the prompt striking of an arc cathode at such an electrode, the methods already described as effective for the glow may be used.

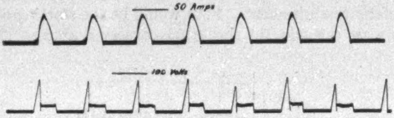

FIG. 1—OSCILLOGRAM SHOWING INSTANTANEOUS VOLTAGE AND CURRENT OF IGNITING ELECTRODE

However, in this case, an additional possibility exists. The density of ionization of the already existing discharge may be raised to so high a value adjacent to the electrode that even with low applied voltage, the positive ion current density will be so large that there will be prompt occurrence of a cause for transition to an arc cathode. This is the method used in the Deion circuit breaker[14] for striking new cathodes on the many plates in the deionizing chamber. The arc which is first drawn at separating contacts is driven by a magnetic field up into slots in the plates, where the reduction of arc section so increases the density of ionization that arc cathodes at once form on the plates.

The authors have also successfully applied this method to the striking of an arc cathode to a mercury electrode in an evacuated vessel. An arc from a separately heated thermionic filament cathode was started, but it was compelled to take a constricted path close to the mercury, thus causing the density of ionization to be very high there. A small voltage difference between the mercury and the discharge would cause the prompt formation of an arc cathode on the mercury.

## IV. THE LIGHT CONTACT ARC STARTER

A form of arc cathode starter of the separating contact type devised by the authors deserves special mention, because to a considerable degree it was free from the inertia difficulty of ordinary separating contacts. A small section pointed tungsten rod was placed in a mercury arc tube so that it dipped slightly to a depth of about one millimeter below the mercury surface. On sending sufficient current through the rod, the cathode of an arc was promptly started at the rod-mercury junction, and this starting could be regularly repeated sixty times per second. The explanation is believed to be as follows:

The current through the rod heated the rod-mercury junction, but the temperature had only to rise to that at which mercury has a vapor pressure of one millimeter, that is, about 125 deg C when a film of vapor would form around the rod, separating it from the rod, and starting an arc cathode on the mercury. In the particular tube used, when such an arc cathode started, the current was diverted to another anode and the arc cathode moved on the mercury surface away from the rod junction. With the current diverted from the rod, the film of vapor around the rod point promptly condensed, so that the starter was ready for a repetition of the process within a sixtieth of a second.

With an immersion of one millimeter, about 200 amperes was necessary for regular striking of the arc. With less immersion, less current could be used, but with the lesser immersion the mercury would sometimes be thrown mechanically out of contact with the rod and would require several sixtieths of a second to return and make contact again.

## V. THE NEW ARC STARTER

In attempting to develop a starter of the type of the preceding section and also of the type mentioned at the end of 3 in section III, it was discovered that a rod of relatively high resistivity partly immersed in mercury had very extraordinary properties with respect to the initiation of arc cathodes on the mercury surface. The first observations were made on a carborundum crystal. It was found that about ten amperes flowing through the crystal would start an arc cathode, and unlike the tungsten rod of the previous section, this current magnitude for starting the arc cathode varied very little with the degree of immersion of the crystal. The voltage required for starting varied with the length of the crystal above the mercury and was less than 100 volts for moderate lengths.

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[14] Slepian, TRANS. A.I.E.E., 48, 523, 1929. Dickinson and Baker, TRANS. A.I.E.E., 48, 528, 1929.

The starting of the arc was extremely regular and reliable. Fig. 1 shows an oscillogram of operation of a mercury pool cathode vapor tube with such a starter. The starter electrode was connected to the anode of the tube through an auxiliary external rectifier, and the whole was placed in an alternating current circuit. As will be seen from the oscillogram, in each half cycle of polarity proper for sending current through the external rectifier, an arc was started in the tube.

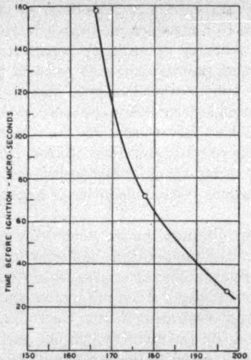

Fig. 2—Curve Showing Variation of Mean Time for Ignition with Voltage

This extraordinary property for starting an arc cathode was found to be generally enjoyed by materials of considerable resistivity. Thus similar results were obtained with starter rods made of lightning arrester resistor material (clay, lampblack mixtures), globar resistors (special carborundum heating elements), galena and ferro-silicon.

No wasting away of the starter rods could be observed even after long periods of operation. Some rods on life test have now been operating sixty times per second, 24 hours per day, for over seven months with no observable deterioration.

The mercury pool was not an essential element in the operation of the starter, as regular operation was obtained with a starter rod partly buried in solidified tin, as well as with a molten tin cathode. Operation was obtained also in air at atmospheric pressure.

The time required for the formation of the arc cathode after the application of the necessary voltage was found to be extremely short. This was investigated with the cathode ray oscillograph by W. E. Berkey. The following results are typical. For a resistor rod of $\frac{1}{8}$ in. diameter in mercury dipping $\frac{1}{4}$ in. below the surface and extending $\frac{1}{2}$ in. above the mercury, the minimum voltage for starting the arc before the rod would heat up appreciably was found to be approximately 130 volts. A sudden application of 250 volts would start the arc within less than five microseconds. As the voltage was reduced, longer time delays between the application of the voltage and striking of the arc were observed. These times varied considerably in test repetitions. Fig. 2 shows the average variation of the mean time with voltage.

## VI. Observations Bearing on the Theory of the New Starter

The insensitivity of the new starter to the degree of its immersion in the mercury indicated that its operation did not depend upon an actual breaking of contact with the mercury. This is confirmed by the operation of the starter buried in solidified tin, and it was also confirmed by operation obtained where permanent electrical contact below the surface of the mercury was insured by means of a tight metal clamp, and also by a copper sprayed portion of the rod below the mercury surface.

When operated just below the voltage required for regular operation, frequent tiny sparks would be observed at the mercury-rod junction. This suggested that the seat of the phenomenon resided at the mercury-rod junction, and also suggested that the operation might take place in roughly two stages, each stage setting different requirements. First would be the starting of a tiny arc cathode, the tiny sparks observed above. This would call for a very high electric gradient, or very large concentrations of energy to effect a thermal explosion at the mercury-rod junction similar to what occurs at the last contact point of separating contacts. Second would be the building up of the small current flowing from this tiny arc cathode to an arc current sufficient to short circuit the rod to the holder or another anode. This would call for the ability of the side of the rod immediately adjacent to the tiny "spark" or arc

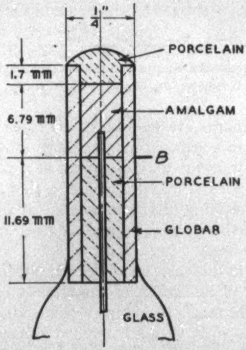

Fig. 3—Diagrammatic Sketch of Apparatus Used to Illustrate the Necessity of a Voltage Gradient for Ignition

cathode to carry considerable current as the anode of an arc.

Both of these requirements seem to call for the existence of an electric gradient down the rod to the mercury-rod junction. The necessity for such a gradient is beautifully illustrated by some experiments of L. Smede.

As illustrated in Fig. 3, a hollow cylindrical starter made of globar was used. Good contact with the internal surface of this cylinder was made up to a level *B* by means of an amalgam. The electrical connection to the amalgam was brought in under the mercury and of course was insulated from the mercury. A barometric connection permitted the mercury level to be raised and lowered. The voltage required by the starter for regular operation was observed for different levels of the mercury. The results are shown in Fig. 4.

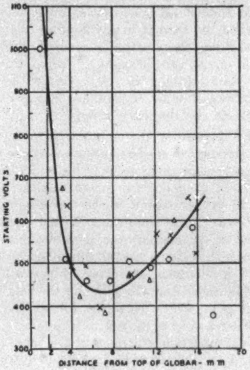

FIG. 4—CURVE SHOWING VARIATION OF IGNITION VOLTAGE WITH LENGTH OF IGNITING ELECTRODE

The impressed potential existed between the internal amalgam and the external mercury. When the mercury level was considerably below *B*, there would be current flow down the cylinder to the mercury from above, and therefore a gradient down the starter to the mercury. As the mercury level approached close to *B*, more of the current would flow across the cylinder wall to the mercury junction, and less down the cylinder wall. Hence for a given voltage, the gradient down the rod would be lessened. Hence if a gradient of a definite magnitude is necessary down the starter at the junction, the voltage required for starting should rise rapidly as the mercury level approaches *B*. This, the curve of Fig. 4 shows to have been actually the case.

## VII. THEORY OF THE NEW STARTER

The observations of the previous section suggest that with respect to voltage and energy concentration, conditions at the starter rod-mercury junction must be similar to those occurring at the last contact point of separating contacts. Electrostatic theory shows that this is the case. Fig. 5 shows the equipotentials and current flow lines for a slab of starter material with parallel plane sides and dipping down a great distance into the mercury. This field distribution is taken from Maxwell "Electricity and Magnetism," 3d edition, Art. 193, p. 297, and assumes that the electrical resistivity of the mercury is negligible compared to that of the starter material. The current and voltage concentration at the mercury junction are quite clear.

From the mathematical formulas of Maxwell in the reference just given, we calculate that the potential gradient along the starter side near the mercury junction is given by

$$\frac{dV}{dx} = \sqrt{\frac{d}{2}}\,\frac{X\infty}{\sqrt{x}} \qquad (1)$$

where $d$ is the thickness of the slab, $X\infty$, the gradient along the slab far from the junction, and $x$, the small distance from the junction at which the gradient $\frac{dV}{dx}$ exists. According to this formula, the gradient, and with it the current density, becomes infinite at the junction where $x = 0$.

Of course, the formula (1) may be considered as applying only so close to the junction as the material may be considered continuous. If we assume that we may consider the material continuous down to atomic distances, that is down to $x = 10^{-8}$ cm, and if we take the slab thickness as 0.5 cm, we have for the gradient at the junction,

$$\frac{dV}{dx} = \sqrt{\frac{0.5}{2}}\,\frac{X\infty}{\sqrt{10^{-8}}} = 0.5 \times 10^{4}\,X\infty \qquad (2)$$

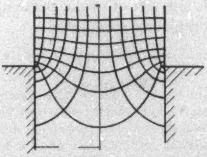

FIG. 5—DIAGRAM OF EQUIPOTENTIAL AND CURRENT FLOW LINES IN A SLAB TYPE IGNITING ELECTRODE

If we adopt as our criterion for the starting of an arc cathode, the appearance of a gradient of $10^6$ volts per cm at the junction, we have for gradient, $\frac{dV}{dx}$ remote from the junction

$$X\infty = 200 \text{ volts per cm} \qquad (3)$$

Actually, less than 100 volts per cm were sufficient for starting an arc cathode with the materials tested. It seems likely that other phenomena peculiar to the carrying of current across contacts appear also at the junction, such as transition films of high resistivity, or the drawing up of small particles forming bridges, as suggested by Holm.[15]

The first requirement for the starting of an arc cathode at the junction then seems to be the impressing of a gradient, $X_\infty$ of the order of 100 volts per cm along the starter rod. This practically sets a lower limit to the resistivity of the rod material, since with ordinary metals and reasonable rod dimensions, the current required to maintain such a gradient would be enormous. We may perhaps set $10^{-2}$ ohms per cm$^3$ as the practical lower limit of resistivity of a starter rod of reasonable dimensions.

The requirements of the second stage of the formation of the arc, however, set an upper limit to the resistivity of the rod. The tiny arc which forms at the junction must grow to a magnitude sufficient to short-circuit the rod. Since the tiny arc first flows to the rod side as anode, the resistivity of the rod must be low enough to permit the flow of sufficient current through the rod side without requiring excessive voltage. Actually, it was found that the voltage required for starting increased with the resistivity of the rod material. We may probably set a few thousand ohms per cm$^3$ as the upper limit for the resistivity of the starter rod.

*Applications of the New Starter.* Applications of the new starter will be obvious to those familiar with grid controlled gas tubes. In such tubes, until now, an arc cathode was permanently maintained by a separately heated thermionic cathode or a keep-alive arc. The starting of an arc to a main anode was then controlled by a grid. Now the permanent arc cathode and control by the grid may be eliminated, and the starting of the arc to the main anode effected and controlled entirely by the new starter. Thus many of the problems associated with the use of grids, particularly for large currents, are completely eliminated.

## Discussion

**H. E. Edgerton:** An arc starter is used at the Massachusetts Institute of Technology for stroboscopic studies of the angular oscillations of synchronous machines, and for taking high speed motion pictures on continuously moving film whereby the starting is accomplished by means of a suddenly-applied high voltage on an external grid or starting band which is located close to the junction of the mercury and the glass. The necessary high voltage is obtained easily and accurately timed by a condenser discharge through a grid-controlled gas-filled tube, such as the thyratron, and a step-up transformer. Further descriptions of the arrangement are contained in an article in the *Review of Scientific Instruments*, October, 1932, p. 535, by K. J. Germeshausen and the writer.

The cathode spot always appears at the junction of the glass and the mercury when an external starter is used. Small spots are seen there even when the anode is disconnected, somewhat as described by the authors. These facts indicate that the starting mechanism may be similar to that described by Slepian and Ludwig, namely, the establishment of a high potential gradient.

The authors have made a valuable contribution to the pool type of mercury-arc tube, and this new starter may aid us in our efforts to get accurately-timed high-speed stroboscopic light.

**W. M. Goodhue:** The physical condition existing in a grid-controlled mercury-arc rectifier or inverter tube has always seemed strained or abnormal for an arc, particularly in an inverter where the anode is positive most of the time *in which the current is not flowing* from anode to cathode. This is an unstable condition and since the cathode is always active, there is always the possibility of the equilibrium being upset by stray ions striking an arc with consequent loss of grid control. The use of the new method described in the paper will tend to remove these strained conditions, since the cathode hot-spot emission has ceased when the current is not flowing. As a consequence stray ions reaching the electrodes are not likely to cause a "misfire," that is, one tube firing at the wrong time and another tube of the circuit failing to fire. Under these conditions, stability exists at the anode, the cathode is acting as a rectifying negative electrode, and the grid is absent.

As stated by the author, the elimination of the grid is an advantage in designing the anode structure. At present, the small glass bulb mercury-arc tubes seem to have lost popularity, due to the necessity of tilting the bulb for starting, and the annoyance of restarting in case of failure of the power supply, unless expensive automatic tilting equipment is used. Also the lack of voltage control of the mercury-arc tube means a disadvantage in comparison with a field-rheostat controlled motor-generator. The successful development of the new device will remove both of these disadvantages and should bring the small mercury-arc tube back into popularity. However, for voltage control, only single-anode tubes can be employed.

An important question concerning the new starter which replaces grids, is the deionization time required for the hot-spot to become inactive. Has the author performed any qualitative or quantitative experiments which would indicate the order of magnitude of this? Another factor which requires consideration is the power that the new starter may require, which may be 1,000 watts or more. This power is much larger than is required by grids except in very large sizes of tube. Is all this power lost as heat in the ignition circuit or is there a possibility that some of this power may be utilized to diminish the cathode drop of the main arc, and therefore cannot all be considered a loss chargeable to ignition? Would it be possible to diminish the ignition power by the use of a starter voltage wave form specially peaked as for example by an auxiliary, saturated transformer so that the starter functions only during the ionization period? After such ignition the arc would maintain itself during the active half cycle.

In addition to describing this particular method of ignition, the paper is very useful to those interested in the subject in that it describes concisely both the physics and application of the several older methods of arc ignition.

**R. E. Hellmund:** In discussing the theory of the new starter, the authors have assumed a smooth surface for the starter and they have shown that with certain resistance values the voltage and current concentration at the starter-rod mercury junction is such as to favor the formation of an arc. In practise, conditions are likely to be even more favorable due to the fact that the starter-rod does not have a smooth surface but a rough contour somewhat as indicated in Fig. 1. The cohesion of the mercury most likely does not permit it to adhere closely to the rod surface in the crevices. This means that there will be point contacts such as at (*a*) and (*b*), a condition which of course brings about much greater voltage and current concentrations than indicated by the formulas in the paper. Instead of having direct contact as in Fig. 1, we may, of course, have contact through small particles as briefly indicated by the authors and somewhat as

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15. R. Holm, *Wiss. Veröff. d. Siemens-Konzern*, X, 4, 1931.

shown in Fig. 2. Here again the cohesion of the mercury is instrumental in creating point contacts.

A certain similarity in the contact phenomenon just described and the latest hypothesis on contact phenomenon described in a paper by Ludwig and Baker[1] and the discussion which I contributed at the time, is quite obvious.

Figs. 1 and 2 shown here seem to indicate the reason for the absolute reliability of the starter-rods in their functioning. If we assumed, for instance, that the phenomenon first takes place at (*a*) but is not sufficient to create a sufficiently sustained cathode spot, another spot is immediately available at a second point (*b*), etc. Thus proper operation is always assured.

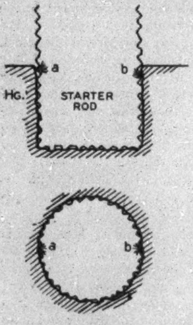

FIG. 1

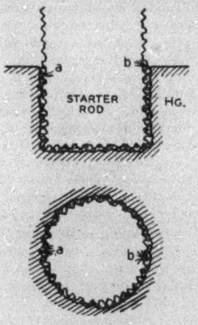

FIG. 2

**D. D. Knowles:** Engineers are familiar with the existing types of grid-controlled gas and vapor filled tubes known under the trade names grid-glow tube, thyratron, trionode, etc. These tubes usually made with hot filament cathodes in an atmosphere of mercury vapor, or one of the noble gases such as neon, argon or helium are splendid devices for the control of relatively small amounts of power and for performing various automatic functions where speed of response, silent operation, extreme sensitivity, or innumerable operations without deterioration are required. They are especially well suited to handle relatively small currents, say up to 100 amperes, at voltages even as high as 20,000 to 30,000 volts.

For power conversion purposes and the control of heavy industrial apparatus, however, they have 3 distinct limitations:

1. The overload capacity consistent with long life is limited. This is due to the fact that the cathode has a definite capacity to emit electrons, this capacity depending upon the type of coating, the operating temperature, and the area. Any current in excess of this limiting value damages the tube to an extent depending upon the overload and the length of time it exists.

2. Considerable energy is required to maintain the cathode at its operating temperature, the actual value, of course, increasing as the size of tube increases.

3. A considerable time is consumed in putting these tubes into service. This is especially true of large tubes and is due to the time required for the filament to reach operating temperature. In some tubes this delay is as much as 30 minutes.

An obvious solution to at least 2 of these limitations would seem to exist in the use of a mercury pool cathode instead of a hot filament. When this is attempted, certain difficulties immediately appear. To begin with, the conventional pool requires a keep-alive arc which means a considerable amount of energy for excitation and complications in the circuit. It also is necessary to provide a means for starting the keep-alive arc. Such means are at the best cumbersome and expensive. What is even more important, the presence of ionization from the keep-alive arc makes it difficult adequately to control the main discharge by means of a grid. These difficulties appear to be eliminated by the igniter electrode described by Messrs. Slepian and Ludwig.

The usual starting mechanism and keep-alive is eliminated because the igniter electrode starts the arc on each positive half cycle.

Whereas the grid in a grid-controlled tube is varied in phase to *allow* the arc to start at a predetermined point in the cycle, the igniter voltage in the new tubes may likewise be varied in phase to determine the point in the cycle at which the arc will be *ignited*. The outward effect—the change in average current output with phase angle, is therefore the same.

There is no delay in starting, such as that required to heat a filament, and the large overload capacity characteristic of mercury pools is, of course, inherent.

It is not surprising, of course, that such a device should have some limitations. In small tubes its utility is somewhat limited at least for the present, by the fact that the maximum current required in the control circuit is of the order of amperes instead of microamperes as in grid controlled tubes.

It is obvious also that a glass tube containing a pool of mercury must be handled with a little more care than is necessary with other types. This objection, however, is not very serious as is proved by the successful use of mercury pool glass rectifiers in this and other countries.

Considering the advantages and disadvantages of this new development, however, it appears beyond any doubt, that a new line of tubes employing this principle will very shortly become one of the most valuable members of the industrial tube family, thus beginning a new era in the conversion and control of power by electronic means.

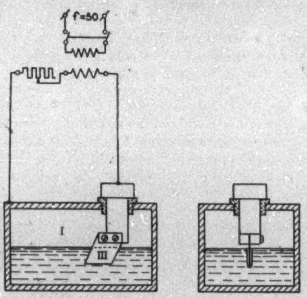

FIG. 3—SINGLE-ANODE MERCURY ARC RECTIFIER WITH IMMERSED ELECTRODE

**Othmar K. Marti:** This investigation of various means for initiating a cathode arc is of great value. In this connection, I would like to call attention to some earlier work along this line.

The initiation of an arc by the use of a high-resistance electrode partly immersed in the mercury cathode was proposed in connection with the early work on the mercury vapor lamp, mention of this being made in British patent No. 13,084, dated June 9, 1904, by Butler-Burke.

In connection with the investigation of cathode phenomena, experiments with a tungsten electrode, partly immersed in mercury and producing a cathode arc, were made in the laboratory of Brown, Boveri and Company, Limited, of Baden, Switzerland, of which an abstract was published in *The Brown Boveri Review* for November, 1929, pp. 303-305, in an article by Mr. A. Gaudenzi. Fig. 3 is a reproduction of Fig. 1 of this article. In it, *III* is the tungsten electrode, 0.3 mm thick, partly immersed into the mercury cathode pool of vessel *I*. When current was passed through the electrode and the mercury, the tungsten electrode became heated, vaporizing the mercury adjacent to it, and producing a layer of mercury vapor between the electrode and the mercury, thus breaking the contact, and producing an arc. The total voltage drop in this arc was approximately 10 volts, which consisted entirely of the cathode drop. It would be interesting to know what voltage drop was observed by Messrs. Slepian and Ludwig when making their investigation.

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[1] *Influence on Commutation of Brush Contact Drop*, A.I.E.E. TRANS., Dec. 1932, p. 959.

According to an oscillogram in the article by Gaudenzi, the apparatus acted as a rectifier, permitting currents up to 230 amperes to flow in only one direction, during the positive half-cycle, and blocking them during the negative half-cycle. It is conceivable that such a device could be used as a rectifier with a very low arc drop (10 volts). In the experiments it was found, however, that the rectifying action ceased when the inverse voltage during the negative half-cycle exceeded 100 volts, so that the application of this apparatus as a rectifier would be limited to low voltages.

The experiment was made with a 50-cycle supply, and, according to the oscillogram in the article, the current flow started regularly every cycle.

The controlling of the point in the cycle at which the main arc to the anode is started, by timing the ignition of the cathode arc, as suggested by the authors, was proposed by P. H. Thomas as early as 1905, as is disclosed in some of his patents.

We would like to take issue with the statements made in the last paragraph of the paper, which seem to infer that unsolved and difficult problems are associated with the use of grids for controlling the firing of the main anodes, and that the method as proposed by the authors would eliminate such problems. In the first place, in the rectifiers manufactured by the company with which I am associated, no difficulties have been experienced in controlling the firing of the anodes with properly designed grids, and no difficulties were experienced with their design or construction. In the second place, it seems rather premature for the authors to state that no difficulties will be experienced in the commercial application of the method proposed by them for controlling high-current rectifiers. In the third place, it seems to be apparent that their method is applicable only to mono-anodic rectifiers, and could not be applied to poly-anodic rectifiers, where the cathode arc burns continuously. It also is evident that more power will be required for controlling the firing of anodes by the method proposed by the authors than with grid control, for which only a small fraction of an ampere, at 100 volts or less, is required to control the firing. The ratio of the controlled power to the controlling power therefore is greater with grid control than in the method proposed by Messrs. Slepian and Ludwig.

**A. W. Hull:** We have checked some of the values reported in this paper, using thyrite as the semi-conductor. For the sample of thyrite used, an average voltage gradient of 600 volts per cm gave reliable starting. This is consistent with the values given by the authors.

This method of initiating arc cathodes puts at our disposal an additional means of control over vacuum arcs, which is sure to find valuable applications.

**J. Slepian and L. R. Ludwig:** The question of deionization time which Mr. Goodhue raises has a somewhat different significance in the igniter-controlled tube than in the usual grid-controlled tube. In the latter, a certain time is necessary for the ion density in the neighborhood of the grid to fall to so low a value that the grid is able to prevent the re-establishment of the arc to the anode. In the igniter-controlled tube, it is the cathode spot of the arc itself which must disappear during the period of reversed voltage. With a cold cathode, as in the mercury pool arc, this cathode spot disappears extremely quickly. Our own experiments indicate that this disappearance takes place in less than a few microseconds. However, this does not mean that high voltage can be applied to the tube immediately after the disappearance of the cathode spot, since there always is the probability of "backfire" and the establishment of a new cathode spot. The probability of backfire is large while the residual ionization is large, and the probability of backfire decreases to zero as the density of residual ionization decreases to zero. Thus, the question becomes—how long does it take for the ion density to fall to so low a value that the probability of backfire is negligible? This question has not yet been investigated in careful detail, but our first experiments indicate that a few hundred microseconds will be more than enough.

As Mr. Goodhue mentions, the instantaneous power in the igniter is large compared with that required by a grid, but the mean power can be made small by using suitable circuits which will supply this power only at the moment it is needed, and only until the arc is struck, but even with these means, the power required by the igniter probably will be larger than that used by a grid. For small power applications this may be a considerable disadvantage for the igniter, but for large powers we do not believe that it is important. The power consumed by the igniter has no effect upon the arc drop in the vessel. The cathode spot of the arc moves away from the igniter as fast as it is struck and during most of the half cycle may be a centimeter or more distant from it.

The account of the work by Gaudenzi given by Mr. Marti is very interesting, but, of course, is not an example of striking the arc by means of a high resistance igniter electrode. It comes rather under the classification "the light contact arc starter" which is described in section IV of the paper. The voltage drop which is observed when the arc is started by the igniter and flows to the igniter holder is about 10 volts.

Mr. Marti seems to be extremely sensitive to any suggestion that there are any difficulties in connection with rectifiers or the application of grids to rectifiers.

The only place where problems are mentioned in the last paragraph with which Mr. Marti takes issue is in the last sentence "thus, many of the problems associated with the use of grids, particularly for large currents, are completely eliminated." We do not say that these problems are insoluble or even that they are not yet solved, but merely that there are problems. Mr. Marti himself admits that, when he requires that his grids be "properly" designed. Such proper design must certainly be for the purpose of preventing some difficulty which otherwise would ensue. Does Mr. Marti suggest that the heating of grids and the rise in the arc drop which they produce present no problems to the designer?

We do not state, as Mr. Marti says, that no difficulties will be experienced in the commercial application of the new method for controlling high current rectifiers. We simply state that elimination of the grid certainly eliminates many of the problems relating to the grid. Of course, the new igniter introduces problems of its own, but we believe that for high power purposes, these problems can be solved in a better fashion than the problems imposed by the use of the grid. Our further experience with the igniter is confirming this belief.

As mentioned heretofore, the power required for operating the igniter will be much larger than that required by a grid. However, if we charge against the grid, the power lost due to the increase in arc drop which the grid produces, then the situation is reversed. The igniter then dissipates less power than the grid. The question as to how much power is required to control the igniter does not seem to us to be a very important one for large power applications. For example, for a 1,000-kw controlled rectifier, the question as to whether the igniter takes 1 kw or 1 milliwatt, seems to us to be very less important than the degree of reliability and sturdiness of the controlling device.

# Applications of Harmonic Commutation for Thyratron Inverters and Rectifiers

BY C. H. WILLIS*
Member, A.I.E.E.

***Synopsis.**—The problem of commutation in thyratron rectifiers and inverters is discussed and a method of using a harmonic circuit of reduced kva to force commutation is described.*

*By the aid of harmonic commutation, inverters can be operated to supply lagging loads and rectifiers can be phase controlled in the leading quadrant. A rectifier which is phase controlled 90 degrees leading becomes equivalent to a synchronous condenser and may be used for power factor correction.*

*A duplex type of circuit is described which enables a polyphase inverter to produce a sinusoidal voltage and current, and permits a rectifier to draw a sinusoidal current from the a-c system.*

*The inverter is shown to differ from a synchronous converter only in that the sum of the a-c and d-c armature reactions of the inverter must always be zero. By providing two sets of tubes in the inverter, one on the unity power factor axis and the other on the zero power factor axis, a crossed axis inverter is developed which will furnish a sinusoidal current and voltage for all conditions of load.*

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## INTRODUCTION

COMMUTATION has not been one of the problems to be solved in the development of the mercury arc rectifier. The unidirectional conductivity of the arc, in combination with the variation of the phase voltages, provides an inherent and entirely satisfactory means of commutation for purposes of simple rectification. This process may be designated by the term *phase commutation.*

When the rectifier is provided with thyratron grids, and operated as an inverter for supplying alternating current, phase commutation as used for rectification, may still be employed, provided the load supplied by the inverter has a leading power factor. Phase commutation in an inverter is, however, not so satisfactory as in the case of a rectifier because it lacks inherent stability, and because commercial loads seldom if ever have a leading power factor.

The problem of commutation as presented by the inverter is quite similar to the familiar problem of commutation in continuous-current motors, because of the fact that the thyratron grids are not able to interrupt the current through the arc, but are only able to maintain an open circuit once the current has been stopped.[1] Early in the history of the d-c motor the commutating pole was developed as an aid to commutation and these have proved indispensible in modern machines.

A method of commutating thyratron equipment has been developed which is closely analogous to interpole commutation in continuous current machines. This method of commutating thyratron apparatus employs a harmonic of the fundamental a-c frequency and has therefore been called "harmonic commutation."

A description of *harmonic commutation* may be found in the December issue of the *General Electric Review.*[2] Since this method of commutating inverters and rectifiers has been described only recently, its general features will be briefly summarized before giving certain applications of this type of commutation to inverters and rectifiers.

## HARMONIC COMMUTATION

One method of applying harmonic commutation is illustrated in Fig. 1, which represents the positive commutating transformer $T$ of a six-phase inverter with the thyratron tubes $A$ to $F$ inclusive. At some instant the continuous current is entering through tube $A$ and the commutating voltage may be assumed as shown by the arrow $e_c$. If now thyratron $B$ is fired, the voltage $e_c$ will transfer the continuous current from tube $A$ to tube $B$. After tube $B$ has been conducting for 60 electrical degrees the commutating voltage $e_c$ will have reversed because it has triple frequency, and $e_c$ will then serve to commutate the current from tube $B$ to tube $C$. Thus the harmonic voltage of the commutating transformer may be used to commutate each tube in succession.

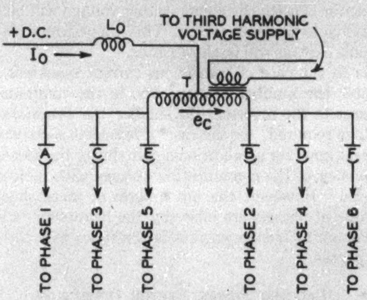

FIG. 1—ELEMENTARY CIRCUIT FOR HARMONIC COMMUTATION

The only condition necessary for satisfactory commutation is that the commutating voltage $e_c$ shall exceed any difference in phase voltage between the tubes under commutation for an interval sufficient to permit the current to transfer and the tubes to deionize.

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*Associate Prof. Elec. Engg., Princeton University.

1. For references see bibliography.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

An excessive commutating voltage causes no serious trouble as in the case of commutating poles, because the unidirectional conductivity of the tubes prevents a reverse current, or over commutation.

Any convenient source of voltage may be used to produce the harmonic commutating voltage. A simple and economical method is secured by connecting a static capacitor across the commutating transformer. A portion of the direct current must then flow through the capacitor, and this builds up a voltage opposing the current flow, and therefore in the proper direction for commutation. Since the direct current flows alternately from opposite ends of the commutating transformer, a capacitor across the commutating transformer provides a voltage of triangular shape as shown in Fig. 2. The maximum voltage $E_c$ coincides with the instant of commutation, and the interval $2\alpha$, as shown in the figure represents the conducting period of one tube. When a capacitor is used, the commutating voltage will be proportional to the load current. This is a desirable feature in some cases as will be shown later.

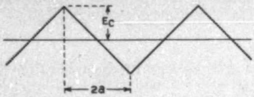


FIG. 2—WAVE SHAPE OF COMMUTATING VOLTAGE PRODUCED BY A STATIC CAPACITOR

As in the case of continuous-current machines, the greater the number of segments, in the commutator, (phases in the inverter) the smaller the commutating voltage required. In the case of *harmonic commutation* there is however an additional gain due to the increased frequency of the commutating voltage with increasing phases. However, the advantages of increasing the number of phases, are offset by the increasing ratio of maximum to average current in the tubes with increasing phases.

### LAGGING POWER FACTOR OPERATION

In discussing the performance of an inverter when supplying a lagging load the operation becomes rather involved. Phase commutation is definitely eliminated as a method of commutation, because this will operate only in the leading quadrant for an inverter. When harmonic commutation is employed, we must provide a commutating voltage $e_c$ which exceeds the difference in phase voltages $e_p$ for an interval sufficient to permit commutation. However the problem of supplying a lagging load from an inverter is more involved than the simple matter of commutation. It is convenient to resolve the problem of lagging loads into two cases:

1. Where the inverter is feeding a system whose voltage wave shape is fixed and practically independent of the current wave as in the case of rotating machinery.
2. Where the voltage wave of the system is a function of the current wave and therefore may become distorted by the current.

### LAGGING POWER FACTOR OPERATION IN PARALLEL WITH SYNCHRONOUS ROTATING MACHINERY

The simpler case where the voltage wave form is definite, corresponds to an inverter operating in parallel with synchronous machines. In considering this case we must bear in mind the fundamental transformer relation that the sum of the primary and secondary load currents in any transformer must be zero at all instants. (Neglecting the exciting current.) When applied to the polyphase inverter network shown in Fig. 3, this principle of transformer operation requires that the output current of the inverter shall be symmetrical about the axis of conduction of the tubes. This idea is quite important for an understanding of the behavior of an inverter when supplying lagging loads. Stating this fact differently, we see that since the load currents are drawn from the d-c circuit, the output a-c currents must at any instant be symmetrical about the axis on which the continuous current is supplied. If we compare the inverter to a synchronous converter we find that the condition just stated is equivalent to stating that the sum of the a-c and d-c armature reactions in the inverter must at all instants be zero.

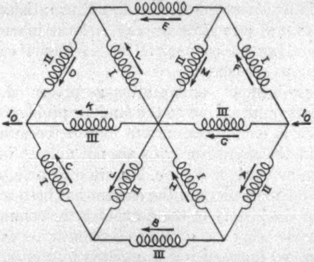


FIG. 3—RIGID 6-PHASE INVERTER NETWORK

This may be illustrated for a six-phase network composed of three separate transformers by referring to Fig. 3. If we represent the currents by the letters as shown, it is easy to prove that

$$A + M + J + D = F + L + H + C \qquad (1)$$

Therefore the load current of transformer (I) must equal the load current of transformer (II) during the entire interval that the continuous current is entering as shown. However transformer (I) has just been commutated while transformer (II) is next to be commutated. If the d-c supply current be constant, the current wave shown in Fig. 4 is the only current wave form possible per transformer secondary. In any case with a balanced load the current during the interval $t_3$

to $t_4$ must be a repetition of the current during the interval $t_1$ to $t_2$.

If now the axis of conduction of the tubes be shifted with respect to the voltage by changing the phase of the grid supply, the current output of the inverter may be given any phase relation desired as shown in Fig. 4. Here the inverter is shown supplying a current lagging the voltage by an angle $\beta$. An inverter may thus be made to supply load at any desired power factor by merely adjusting the phase of the axis of conduction with respect to the a-c voltage wave. However, once the phase of the axis of conduction has been set, the inverter must supply its current at this power factor and no other.

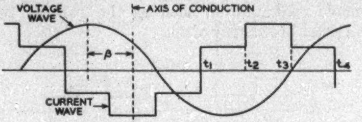


Fig. 4—Current Wave Shape in Secondary of a Network Transformer of a 6-Phase Inverter

When an inverter is operated in this manner it becomes equivalent to a synchronous converter, excited for normal a-c line voltage, with the brush position variable at will. The power factor of the alternating current depends on the brush position, and also the ratio of the a-c to the d-c voltage depends on the brush position, and therefore on the power factor. By the aid of harmonic commutation a tube converter can be commutated through the entire circle of 360 degrees as shown in Fig. 5. We may operate through 180 degrees as a rectifier, using phase control of the d-c voltage in either the leading or lagging quadrants, and we may operate through the entire inverter semi-circle supplying loads at any power factor desired from zero leading to zero lagging. The tube converter differs from the synchronous converter only in regard to armature reaction. In the tube converter the sum of the a-c and d-c armature reactions must at all instants be zero as a consequence of relation 1.

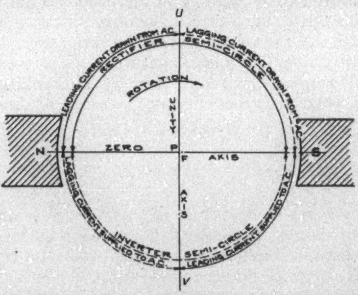
When operating as a rectifier in the leading quadrant the d-c voltage decreases as the power factor decreases. With the voltage approximately zero we may short circuit the d-c output and the rectifier then becomes the equivalent of a synchronous condenser in that it draws a leading current from the a-c system. The commutating kva required here will be a maximum because the difference in phase voltage *ep*, is a maximum at the instant of commutation and opposes commutation. The amount of load is determined by the phase of the grids. If the firing of the grids is delayed slightly the equivalent rectified direct current is increased and therefore the circulating current and kva drawn from the a-c system increases.

## Lagging Power Factor Operation Without Parallel Synchronous Rotating Machinery

The case where the inverter is supplying a load whose voltage wave form is a function of the current wave is further complicated by the fact that the inverter so far described can supply only the current wave form shown in Fig. 4. If now we load this inverter with a load composed of a resistance and inductance in parallel, the voltage wave will be distorted as shown in Fig. 6. The effect of this distortion is to increase the effective value of the voltage and also to make commutation more difficult. With a small amount of lagging load this effect is not serious, but it presents a problem which may be serious in a number of applications.

To illustrate this, we will assume a six-phase inverter whose voltage wave form for phase 1 is shown in Fig. 7A. We will now assume a load which consists of resistance and inductance in parallel. The resistance component of the current is shown in Fig. 7B. The inductive current is shown in Fig. 7C and the total current for some ratio of resistance and inductance is shown in Fig. 7D. The instantaneous power of phase 1 under the conditions of load assumed, is shown in Fig. 7E. With a balanced load the total power must be as shown in Fig. 7F.

The direct current must be supplied at a constant voltage to give the phase voltage wave form shown in Fig. 7A; therefore when the load is partly inductive the continuous current supply, which is proportional to the total power, must be pulsating as shown in Fig. 7F. With loads which are largely inductive the supply current would become actually alternating.


U
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AXIS
S
AXIS
LAGGING CURRENT SUPPLIED TO A.C.
INVERTER
SEMI-CIRCLE
LEADING CURRENT SUPPLIED TO A.C.
V

Fig. 5—Power Factor Circle for Inverter and Rectifier Operation

Of course this ripple in the supply current can be smoothed out with a filter. However this complication of a pulsating power is not inherent in the inductive load but is introduced by the fact that the voltage wave was a stepped wave. A sinusoidal wave of voltage would eliminate the necessity for a pulsating power supply, and be much more satisfactory in many other respects. It therefore appears that the output voltage wave of an inverter must be a close approximation of a sine wave for satisfactory operation under all conditions of load.

## SINE WAVE INVERTER

The cause of the poor voltage and current wave forms is inherent in the fact that the point at which the direct current enters the network advances by discrete jumps rather than by a uniform motion. In order to have uniform motion of the point of entry and yet have a finite number of points of contact (and therefore tubes) it is necessary to have two tubes which are connected to the network on different axes, conduct simultaneously. By varying the proportion of the current carried by a tube we can cause the equivalent point of current entrance to move uniformly from one tube to the next.

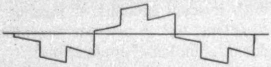

FIG. 6—VOLTAGE WAVE DISTORTION DUE TO AN INDUCTIVE LOAD

One of the circuits which may be employed to accomplish this uniform commutation of the continuous current is shown in Fig. 8. Since the tubes here have been divided into two groups, each group of which will operate as a six-phase inverter, this particular circuit has been called the twin-six.

When tube $A^+$, Fig. 8, is in the middle of its conducting period, the total continuous current is entering through it. The voltage across $C_1$ is then zero and the voltage across $C_2$ is a maximum which we have called $E_c$. If now tube $B^+$ is fired there will be a voltage $E_i$ which will tend to transfer current from tube $A^+$ through the inductance $L$ to tube $B^+$.

$$E_i = \frac{1}{2} e_c - e_p' \tag{2}$$

As condenser $C_2$ discharges and its voltage is consequently reduced, condenser $C_1$ is charged in the reverse direction and therefore the voltage available for transferring current from tube $A^+$ to tube $B^+$ remains approximately constant during the interval in which current is transferring in a given direction. Further, this voltage, $E_i$, increases with $e_c$ which is proportional to the load. Therefore the voltage available for transferring current increases with the current to be transferred and we have approximately the same wave form at all loads. If we make $E_i$ proportional to $I_o$ the wave form will be the same for all loads. The oscillograms shown in Fig. 9 were taken on a twin-six inverter supplying a resistance load. Table I gives the harmonic analysis of the voltage wave of this inverter. The measured value of the current *TIF* was 94, which is not so far from a poor rotating machine.

TABLE I

| | |
|---|---|
| Fundamental | 99.95% |
| 3rd harmonic | 0.9% |
| 5th harmonic | 0.8% |
| 7th harmonic | 0.4% |
| 9th harmonic | 0.9% |
| 11th harmonic | 2.1% |
| 13th harmonic | 1.0% |
| 15th harmonic | 0.8% |
| 17th harmonic | 0.5% |
| Form factor | 1.11 |
| Deviation factor | 7.9% |

Harmonics not given were less than 0.2%

There are several features of the duplex circuit using harmonic commutation such as the twin-six shown above which are worthy of note.

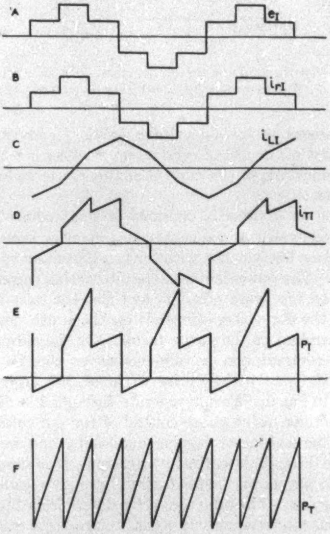

FIG. 7

*A*—Voltage wave shape
*B*—Current wave shape in resistance load
*C*—Current wave shape in an inductive load
*D*—Total current wave for a resistance and inductance in parallel
*E*—Instantaneous power per phase
*F*—Total instantaneous power for 3-phase load or d-c supply current

First, the slow commutation between the two sets of tubes is reinforced by a fast commutation between tubes of one set. Thus we have the normal commutation process reinforced by a reserve process of commutation. In fact one tube may be completely removed from the circuit during operation without a failure of operation. It is hoped that this reserve commutation will make operation more reliable.

Second, anode bombardment should be reduced in this circuit since the current through a tube is gradually reduced to a low value before the inverse voltage is applied, and therefore we should have much less ionization present in the tube at the time of deionization.

Third, the transient voltages incident to rapid commutation are not present in this circuit. For this reason this circuit should be much easier on tubes and transformers than any circuit in which the rate of change of current is very large at times.

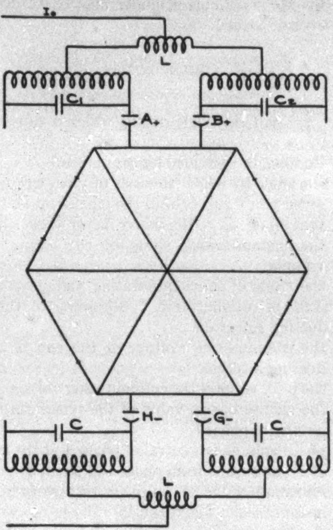

FIG. 8—ELEMENTARY CIRCUIT FOR TWIN-SIX SINE WAVE INVERTER OR RECTIFIER

The commutating voltage required for satisfactory operation of a six-phase full-wave inverter using a static capacitor to produce the commutating harmonic is,

$$E_c = 2\,E_o \sin(\beta + \alpha) \qquad (3)$$

where $E_c$ is the maximum value of the commutating voltage. In the twin-six circuit using static capacitors to supply the commutating harmonic,

$$E_c = \frac{I_o}{4\,f_1 C P} \times 10^6 \qquad (4)$$

where $I_o$ is the continuous current, $f_1$ is the fundamental frequency, $P$ is the total phases, and $C$ is the commutating capacitor on each commutating transformer in $\mu$f.

When the twin-six inverter is supplying a system whose wave form is sinusoidal the best value of the inter-phase reactor depends on the power factor at which the inverter is to supply its load. An exact solution for the best value of $L$ is rather involved. However an approximate value is given by the expression,

$$L = \frac{10^6}{8\,C f_1^2 P^2} - \frac{E_o\,\alpha \sin\beta}{I_o f_1 P} \qquad (5)$$

If we assume unity power factor operation for a 60-cycle twin-six circuit equation (16) becomes,

$$L = \frac{1}{4.15\;C} \qquad (6)$$

where $L$ is in henrys and $C$ is in $\mu$f. A more exact solution than that given in equation (5) may be derived from the circuit relations shown in Fig. 8, but the general solution does not lend itself to a simple numerical calculation of $L$.

The General Electric Company has now ready for test, a 500-kva rectifier using the F.G.41 thyratron tubes and employing harmonic commutation and the twin-six rigid transformer network shown in Fig. 8, to give a sinusoidal alternating current. This rectifier is designed to be supplied from a 4,000-volt, three-phase, 60-cycle circuit and to operate at zero leading power factor as described above.

This apparatus will function as a synchronous condenser and may be given the same load characteristics as a rotary synchronous condenser, but without many of the complications and disadvantages of rotating machines. The rectifier operating as a condenser will lack the ability to hunt and cannot drop out of synchronism. The losses will be lower than those of a rotating synchronous condenser of equal rating.

FIG. 9—OSCILLOGRAM OF TWIN-SIX SINE WAVE IN OPERATION

## VARIABLE POWER FACTOR LAGGING LOADS WITH A SINE WAVE INVERTER

We will now consider the problem of supplying a variable power factor load such as an induction motor from an inverter. We may now employ a duplex type of circuit such as the twin-six circuit described above to eliminate the necessity for a pulsating supply current. However there still remains the difficulty that the alternating currents must at every instant be symmetrical about the equivalent point of continuous current entrance. An inverter supplying a variable power factor load is closely analogous to a synchronous converter operating under similar conditions but with the restriction, noted before, that the inverter is equivalent to a synchronous converter in which the a-c and d-c armature reactions must always exactly cancel. The inverter has no separate field excitation to cancel any difference between the a-c and d-c armature reactions.

With this restriction a rotary converter to supply a variable power factor a-c load would require two sets of brushes operating on different axes. Then as the power factor of the load varied the proportion of the current supplied through a set of brushes would vary correspondingly. Thus if we have brushes on two axes the resulting axis of current supply may be at any point between the axes of the two sets of brushes. For the widest range of power factor variation one set of brushes should be on the axis of maximum voltage and the other set of brushes on the axis of zero voltage.

Returning now to an inverter; if we have one set of tubes operating on the axis of unity power factor load and another set of tubes operating on the axis of zero power factor load, or operating as a synchronous condenser the inverter may supply any load from zero lagging to unity power factor.

In the inverter, as the load becomes more lagging, there will be a tendency for the voltage across arc *VN* Fig. 5, to increase, while the voltage across arc *NU* will decrease. This will result in a circulation of current along the axis *NS* through the tubes which are operating as a condenser. Thus the current in the inverter is automatically divided into two parts and the tubes operating on axis *UV* supply the power component of the current from the d-c system while the tubes operating on axis *NS* short-circuit the wattless component of the current. An inverter as just described, having two sets of tubes on different axes may be referred to as a crossed or quadrature axis inverter.

The chief difficulty encountered in operating a quadrature axis inverter lies in the fact that the commutating voltage of the tubes operating on the zero power factor axis must have a value sufficient to maintain commutation at light loads. For the same a-c wave shape for all loads the commutating voltage of the tubes operating on the unity power factor axis should vary according to the relation

$$E_c' = bI_o' \qquad (7)$$

where $b$ is a constant determined by the condition of satisfactory commutation and $I_o'$ is d-c current necessary to supply the power. The tubes operating on the zero power factor axis should have a commutating voltage which varies according to the relation

$$E_c'' = E_p + bI_o'' \qquad (8)$$

$I_o''$ is the d-c equivalent of the reactive power which must be short-circuited.

With these conditions fulfilled the twin-six crossed-axis inverter will supply lagging loads of any amount and power factor without voltage wave distortion.

The work described above was done in the Research Laboratory of the General Electric Co. The author wishes to express his appreciation of the great assistance given by Messrs. Louis Klauder and G. C. Nonken, in the work described.

### NOMENCLATURE

$\alpha = \dfrac{\pi}{P}$ half the angle during which a tube is conducting, or $\pi$ divided by the phases.
$\beta$ = the angle by which the axis of conduction for a given phase lags behind the maximum voltage in that phase. (*i. e.*, the power factor angle.)
$e_c$ = the instantaneous value of the commutating voltage.
$e_o'$ = the value of the commutating voltage at the instant of commutation. (Beginning of the conducting interval.)
$e_c''$ = the commutating voltage at the end of a conducting interval.
$Ec$ = the peak value of the commutating voltage.
$e_1$ = the instantaneous value of the phase voltage to neutral of phase 1.
$e_1'$ = phase voltage to neutral of phase 1 at the instant of commutation from phase 1 to phase 2.
$E_m$ = maximum value of the phase voltage to neutral.
$e_p$ = instantaneous difference in voltage of two consecutive phases.
$e_p'$ = difference in voltage of two consecutive phases at the instant of commutation.
$E_p$ = the maximum difference in voltage of two consecutive phases.
$E_i$ = voltage available to transfer current from a tube in one set of a twin six inverter to a tube in the other set.
$E_o$ = maximum possible average value of the d-c voltage.
$E_{dc}$ = average value of the d-c voltage. (Phase controlled.)
$E_t$ = maximum voltage across a tube.
$f_1$ = the fundamental frequency of the alternating current.
$f_c$ = the frequency of the commutating voltage.
$I_o$ = the d-c line current.
$I_a$ = the average current through a tube.
$P$ = the number of phases in the inverter or rectifier.
$T_c$ = the time available for commutation.
$T_d$ = the deionization time of a tube.
$T_t$ = the time required to transfer current from one tube to the next.
$\omega$ = the electrical velocity in radians or $2\pi f_1$.

## Bibliography

1. *Gas-Filled Thermionic Tubes*, by A. W. Hull, TRANS. A.I.E.E., Vol. 47, p. 753.

2. "Harmonic Commutation for Thyratron Inverters and Rectifiers," by C. H. Willis, *G. E. Review*, Vol. 35, p. 632.

## Discussion

**P. M. Currier:** This paper should be of particular interest to those who have studied and worked with inverter circuits. As Doctor Willis intimates, circuits using phase commutation are at a disadvantage when one attempts to apply them to loads of commercial power factors. He has shown how by the use of harmonic commutation static equipment can be built that practically duplicates the characteristics of direct or inverted rotary converters, and synchronous condensers.

The sine wave inverter described has particular merit in that the a-c vectors have a continuous, almost uniform, motion instead of progressing by jumps as in some other circuits. The transformer windings appreciate this and do not give the transient voltages which are incident to a jumping vector.

It is of particular importance to note that commutation is given two chances to take place. If the first slow commutation should not function properly for any reason, it is reinforced by a fast commutation at the time the next commutating step occurs.

**W. M. Goodhue:** In discussing the inherent stability of inverters, it should be noted that much depends on the type of high-voltage d-c transmission system used. For example, in a constant-current system, the failure of one tube to operate at the proper instant (misfire) is not likely to cause a heavy short-circuit of the d-c system through the low resistance d-c path of tubes (now firing) and the transformers. Also the employment of a synchronous condenser (with low leakage-reactance and with damper windings), in place of static condensers or harmonic commutation, gives a reserve transient source of almost constant potential due to the inability of the cross-gap flux, which links the damper windings, to change suddenly except by becoming peripheral leakage flux, etc., with very heavy currents. If the grid excitation is fed from this same synchronous condenser, there is no hunting between inverter and condenser.

Two questions are asked in the following:

(1) Will a large load on one phase of an inverter employing harmonic commutation cause interruption of service? (2) Does this circuit require a special grid circuit wave form to prevent uncontrolled rectification and consequent d-c short-circuit when carrying lagging loads?

So far as the d-c or average values of current and voltage are concerned, the tubes of different phases operate in parallel (Figs. 1 and 8), with the result that the d-c voltage of the inverter set is definitely limited to less than the rated peak stresses of the tube (15,000 volts maximum for FG 41, according to *G. E. Review*, Dec. 1932, p. 626, Fig. 8). Therefore, in the opinion of the author, what method should be used to meet commercially the demands of high voltage d-c transmission without employing too many tubes?

The sine-wave inverter of Fig. 8, that is, the twin-six circuit, may be regarded as having twelve phases, since each group of six of the twin sixes are out of phase with each other by 30 deg; also the circuit employs inductance lag for dragging out the commutation period. Could not a simple twelve-phase inverter, employing phase commutation, *with transformer leakage flux between anode coils* to drag out the commutation also produce a passable sine wave of current within its operating range, of leading load, obtained by a synchronous condenser? (Note: with a constant-current d-c system, the alternating current and alternating current voltage may both be constant in magnitude, the phase angle varying with load.)

A constant-current high-voltage d-c system has many advantages in addition to those named above: (1) the prime electrical source consists of alternators; (2) because of the large armature reaction usual with modern alternators, they may easily be inherently constant-current machines rather than constant-potential machines, so that automatic regulators for them should be easier to design than for constant-potential machines as is customary at present and (3) the current need never be suddenly interrupted but by-passed instead, so that the use of circuit breakers is possible with constant current, while with constant-potential direct current a short circuit *on a branch line* will shut down the entire system, since circuit breakers on constant-potential direct current can operate successfully only at zero current.

**A. W. Hull:** The possibility of a gradual, instead of abrupt, transfer of current from one tube to the next, which Doctor Willis has accomplished by his duplex circuit, solves the most serious life problem of sealed-off thyratron tubes, *viz.*, that of the damage done by the ions which are left in the space when the anode voltage reverses. It is well known that these ions delay the regaining of grid control, the so-called deionization time, and that their impact on the anode may initiate reverse current or arc-back; but it is not generally realized that they may be numerous enough to cause severe sputtering of the anode, sufficient to coat over insulating surfaces, impair vacuum, and contaminate the cathode surface.

The following example will show the order of magnitude of this disintegration:

A pair of small phanotron tubes with graphite anodes 2 cm in diameter were operated in a single-phase rectifier at 2,000 cycles, 2,700 volts rms, supplying ¼ amp to a resistance load. At the end of 135 hours they failed from loss of emission, and examination showed that the anodes had been eroded to a depth of 1 mm over their whole surface. This effect is exaggerated at high frequencies, because the anode voltage attains high negative values before the ions have disappeared; but it is important even at 60 cycles. Doctor Willis has shown us how to avoid it by transferring the current so gradually that there are practically no ions present when the anode voltage reverses.

The high ratio of peak current to average current, which Doctor Willis has referred to as partially offsetting the economies of a large number of phases, need not be looked upon as objectionable, nor appreciably more expensive, if the tubes are designed with this in view. It appears that a number of the most useful circuits require a ratio of 12 to 1, and it is probable that future tubes will be designed for this ratio.

**C. W. Lampson:** The General Electric Company at Pittsfield has built a thyratron converter utilizing the twin-six principle and operating at zero power factor. This converter has now been under test for a period slightly over six months. During this time we have had an opportunity to verify the essential correctness of principle of harmonic commutation as applied to a polyphase inverter or rectifier.

One incident in the early stages of the test admirably illustrates the third point which Doctor Willis has made concerning the reduction in transient voltages afforded by the gradual shift of current from one tube to another. The current shifting circuit was so adjusted that the rate of shift was reduced leaving a tube conducting a considerable amount of current at the instant of commutation. Very high transient voltages were immediately in evidence on the tube panels, being sufficient to spark over a two-inch gap between the tube and ground. The restoration of the rate of current shift to normal immediately reduced these voltages to a low value.

Oscillograms taken of the current drawn by this rectifier from the line indicate that it is substantially a sine wave at full load. At lower loads the wave shape is distorted to some extent but means can be provided to maintain this wave shape constant at all loads. Measurements of the loss of the rectifier operating at approximately zero power factor indicate that efficiencies of 97 to 97.5 per cent can be obtained corresponding to a loss angle of

14 to 18 degrees. This efficiency could undoubtedly be bettered in a larger model.

It is particularly interesting to note that the zero power factor rectifier imposes the hardest duty on the tubes that will be obtained in any power device. In an inverter, ability to hold off forward voltage is important. In the rectifier, ability to withstand inverse voltage is important, but in this device both forward and inverse voltages of considerable magnitude must be withstood. The ability of the tubes to operate satisfactorily in this application certainly indicates that successful converters of other types can be built.

The rectifier being continuously variable in amount of leading kilovoltampere drawn and having no moving parts is particularly amenable to automatic control.

**R. G. McCurdy:** The use of vapor discharge devices for rectifiers and inverters creates some very interesting problems for the engineer concerned with the inductive coordination of power and telephone systems.

Two distinct problems are introduced, one concerned with the a-c components in the voltages and currents of the d-c systems, and the other concerned with the departure from sinusoidal wave shape of the voltages and currents on the a-c side. For the d-c side, experience with the mercury arc rectifier has shown that the solution is not difficult. With 6- or 12-phase operation and with filters of practicable cost the a-c components in the d-c system can be reduced to magnitudes which permit satisfactory coordination with telephone systems.

On the a-c side, the problem appears more difficult. In cases where a rectifier forms an important part of the load on a power system or where it is supplied over a circuit of comparatively high impedance at the harmonic frequencies, distortion of the voltage wave shape may be considerable, and noise in exposed telephone circuits may result.

This aspect of the rectifier problem is being actively studied at present by the Joint Subcommittee on Development and Research of the N.E.L.A. and Bell System.

The difficulties with the a-c side of rectifiers have naturally created some concern regarding the possible effects of inverters, looking forward to some of the proposals which have been made for d-c transmission accompanied by inversion and distribution at a-c frequencies at various load centers. It is encouraging to note from the paper that there is a considerable advantage from the standpoint of satisfactory commutation in the inverter when the output current has a reasonable approach to a sine wave shape. Judging from the analysis given in Table I of the paper and the measured value of current *TIF* quoted, some advance has been achieved in this respect over the waves encountered with many mercury arc rectifiers in commercial operation. It seems highly desirable to recognize the inductive coordination aspects of this development in its early stages and well in advance of the commercial application to operating systems.

**H. C. A. Sabbah:** Harmonic commutation has also been applied by the writer.[1] In fact, the criterion given on pages 294 *et seq.*, of the above references shows that all series type circuits can be used to supply variable lagging power factor loads. All polyphase circuits which use interphase transformers come in this class also, if the interphase transformer is shunted by condensers or by a stiff harmonic supply voltage.

The inverter circuit given in Fig. 1 is one which has been worked out by the writer for supplying a load of any power factor. In this circuit the harmonic commutating voltage is supplied to the interphase transformers by the capacitors $C_1$, $C_2$, and $C_3$. Here the capacitors mentioned operate on the 2nd harmonic of the fundamental frequency. It is also interesting to note that these commutating capacitors only have to carry at most ½ of the load current and their size is accordingly reduced. This is due to the fact that they have to carry only the a-c component of the rectified load current per phase. The d-c current is carried by the interphase coils. The fluxes resulting from the d-c currents neutralize in the three phase core of the interphase transformer, which greatly reduces the size and cost of this structure.

Neglecting for the moment the effect on output wave shape, it is only necessary for the purpose of accomplishing practical commutation that the commutating capacitors $C_1$, $C_2$, $C_3$ carry a current of the order of magnitude of the exciting current of the interphase transformer at the 2nd harmonic frequency. This would be sufficient to stiffen the interphase voltage during a period larger than the deionization time of the tubes. From a practical point of view it is desirable to have a good wave shape on an inverter and the writer has found that one of the most economical ways of accomplishing this desirable feature is to connect three capacitors, $C_1'$, $C_2'$, $C_3'$, across the output of the inverter as shown in Fig. 1. The function of these capacitors is to remove harmonics which are causing the wave deformation. To accomplish this purpose they should offer a low impedance to the 5th and higher harmonic currents around the load. The effective value of the sum total of these harmonics is of the order of ⅓ of the load current.

In this circuit current commutation can be made very gradual since the commutating current is only ⅓ of the direct current and the time allowed for commutation may be as much as 60 degrees with a theoretical limit of 240 degrees. With the arrangement as shown, which employs three commutating capacitors, more than one tube can be in a conducting state at one time. This permits us to allow each tube to conduct for a period as much as 240 degrees (see previous reference, page 739). This gives us a good utility factor on the conducting time of the tube and permits them to carry higher momentary loads.

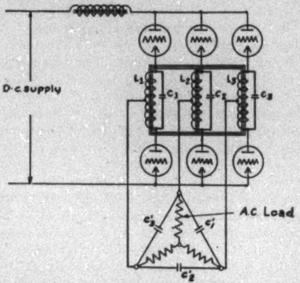

Fig. 1—A Full Wave Three-Phase Inverter Using Second Harmonic Commutation

**C. H. Willis:** The specific questions of Mr. Goodhue may briefly be answered as follows.

1. Any polyphase inverter will operate with a considerable load unbalance. However, when there is no parallel rotating machinery the current unbalance causes a compensating voltage unbalance because there is no energy storage in the inverter. The d-c energy is supplied in a steady stream and therefore the sum of the polyphase circuits must absorb energy at a constant rate.

2. The grid voltage of any inverter must be negative during the entire non-conducting interval of the tubes. Harmonic commutation offers no advantages in this respect.

3. The problem of high-voltage inverter operation may be solved either through the use of higher voltage tubes or by employing series inverter units. This problem is rather in advance of the present stage of development.

4. Any improvement of the wave shape by the use of leakage reactance involves a corresponding reduction of the power factor of the load. This reduction is of serious magnitude where phase commutation is used. It has the further disadvantage that the wave shape varies greatly with the load. The twin-six circuit has the advantage of giving practically the same wave shape for all loads.

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[1] *General Electric Review*, 1931, May, p. 288, October, p. 580 and December, p. 738.

# PREFACE

This final number of Volume 52 of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers is of unusual importance for several reasons:

1. It completes the Institute's published records of technical papers and related discussion for the year 1933.

2. It embraces in a single bound volume the same scope of material that customarily has been included in separate quarterlies, one dated September and the other dated December.

3. It closes the six-year era of QUARTERLY TRANSACTIONS.

4. It contains a comprehensive and generously cross referenced subject index and author index covering all quarterly issues of the TRANSACTIONS for 1933; also includes reports of the Board of Directors for 1932 and for 1933.

In effect, there are in this single bound volume two quarterly numbers of the TRANSACTIONS, embracing material as follows:

1. In the September section (pp. 711 to 944)

   All technical papers and related discussions presented at the Institute's North Eastern District (No. 1) meeting held at Schenectady, N. Y., May 10-12, 1933;

   Part of the papers together with their associated discussion, presented at the Institute's 49th annual summer convention held at Chicago, Ill., June 26-30, 1933.

2. In the December section (pp. 945 to 1153)

   The remainder of the technical papers and associated discussion presented at the 1933 summer convention; 1933 technical committee reports and reports of the Board of Directors for 1932 and for 1933; composite reference index for 1933.

By combining these two quarterly numbers of TRANSACTIONS into this single bound volume, it has been possible to effect some necessary savings in costs without diminishing the material included in the TRANSACTIONS; also to obviate certain delays otherwise beyond control, thus making possible the distribution of the December contents much earlier than has been possible in the past.

As discussed extensively in several articles appearing in ELECTRICAL ENGINEERING during the latter half of 1933, and as contained in notices to all TRANSACTIONS subscribers, the 1934 A.I.E.E. TRANSACTIONS will be issued in December 1934 as a single bound volume embracing the contents of the 12 monthly issues of ELECTRICAL ENGINEERING for that year. By thus obviating the discrepancy that has prevailed between the total contents of ELECTRICAL ENGINEERING for a given year and the contents of the bound volumes of TRANSACTIONS, the annual volume of TRANSACTIONS will become a complete reference record of all technical and related material published by the Institute for the current year.

# The Electrical Characteristics of Impregnated Cable Papers

BY C. L. DAWES*
Member, A.I.E.E.

and

P. H. HUMPHRIES†
Associate, A.I.E.E.

IN CONNECTION with the investigation of ionization in impregnated-paper insulated cables conducted at The Harvard Engineering School under auspices of the impregnated-paper cable research committee of the National Electric Light Association, it was found necessary to determine over a considerable range of voltage gradient, temperature, and frequency, the electrical characteristics of cable papers impregnated with different cable oils and compounds. The impregnation was conducted under almost ideal laboratory conditions so that little if any gas was occluded. When the results of the measurements were rationalized and analyzed, it was found that to a remarkable degree they all conformed to the same general laws. These laws and the analyses of the electrical characteristics into components may appear to be only empirical. However, they are results of some fundamental causes, involving probably molecular and intramolecular reactions. Therefore, aside from any value which the results presented may have as engineering data, they may at some time be of value in confirming or in disproving some more fundamental theories of dielectrics. Moreover, it is found that actual cables when impregnated so thoroughly that they manifest no appreciable ionization, have electrical characteristics comparable to those obtained with these samples impregnated under almost ideal conditions. Hence the characteristics of impregnated cable paper given here are available as standards with which cables may be compared.

## APPARATUS

Each sample consisted of twelve flat circular sheets of wood-pulp paper, each sheet being approximately 6.5 to 6.7 mils (0.165 to 0.170 mm) thick and having a diameter of 15 in. (38.1 cm). Details of the apparatus and method of impregnation are given in bibliography reference No. 2, although minor improvements have since been made. Briefly, both the cable paper and the compound were subjected to a drying process for approximately 9 hr at 105 deg C and at a vacuum better than 2 mm of mercury. For approximately 21 hr longer, during impregnation and after the complete impregnation of the sample, the temperature and the vacuum were maintained at the values stated. Hence, the completed samples should contain, either in absorption or as voids, only the slightest traces of gas.

In these particular tests, three cable oils, widely divergent in their physical characteristics, were used. Compound (or oil) *A* is a light clear oil of low viscosity and is described as follows: "a light oil especially prepared so that amorphous constituents are removed." Its Saybolt viscosities are approximately 250 and 40 sec at 30 and 100 deg C, respectively. Compound *B* is a paraffin base cylinder oil having a Saybolt viscosity of 150 sec at 100 deg C. Compound *C* is of a petrolatum base containing a small amount of rosin (about 5 per cent). The Saybolt viscosity-second characteristics of all three compounds are given in Fig. 3 of bibliography reference No. 2.

All measurements were made on the mutual-inductance power-factor bridge which has been in use in The Harvard Engineering School laboratories for some years past.[3]

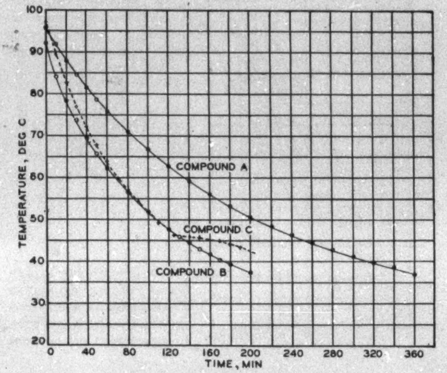

FIG. 1—COOLING CURVES OF THE THREE INSULATING COMPOUNDS TESTED

## COOLING CURVES

It has been found that when compounds are heated to 100 deg C or thereabouts and allowed to cool slowly, the temperature-time characteristic frequently shows an abrupt change, usually near 50 deg C. Moreover, the electrical characteristics of many cable papers impregnated with compounds show abrupt changes or reach minima at or near this temperature. For example, the minimum of the V- or U-curves occur at or near this temperature. (See Figs. 14, 15, and 16 in bibliography reference No. 1; Figs. 4 and 6 in No. 5; pp. 38-46 in No.

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[3] For numbered references see Bibliography.

9; also Nos. 11 and 12.) Possibly this change in slope is due to a change in the molecular structure of the compound which is accompanied by an internal thermal change. Cooling curves for these three compounds are given in Fig. 1. It may be noted that compounds *A* and *B* show no abrupt changes in slope; compound *C* shows such a change at 46 deg C. This may be due to a molecular change in the rosin itself or to an interaction of the rosin content with other ingredients of the compound at this temperature.

## POWER LOSS-VOLTAGE GRADIENT CHARACTERISTICS

As a rule, at room temperature, the power factor and dielectric constant of impregnated paper as functions of voltage gradient are constant.[2] This relationship has been found also by others.[4] Furthermore, in the Harvard laboratories, this relationship has been found true with pyrex and other glasses which are much more nearly perfect dielectrics than impregnated cable papers. When the power factor and dielectric constant do not vary with change in voltage gradient, the power loss must increase as the square of the voltage gradient. When the power loss varies as the square of the voltage gradient, the power loss-voltage gradient characteristics when plotted with log-log coordinates are linear and have a geometrical slope of 2. Such characteristics for compounds *B* and *C* are given in Figs. 2 and 3. In each case the slope of the graph at room temperature (about 20 deg C) is 2. Hence, at room temperature, the power loss in cable impregnating compounds *usually increases as the square of the voltage gradient.*

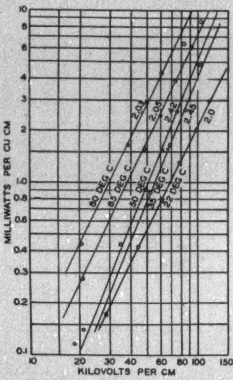


FIG. 2—(LEFT) POWER LOSS - VOLTAGE GRADIENT CHARACTERISTICS OF COMPOUND *B*, PLOTTED WITH LOGARITHMIC COORDINATES

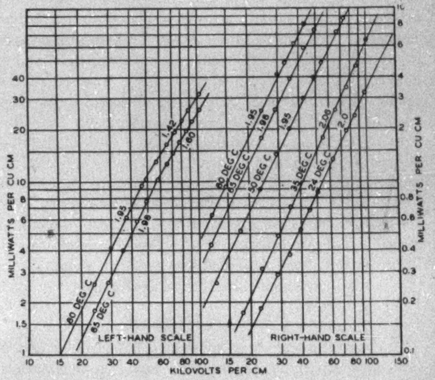


FIG. 3—(RIGHT) POWER LOSS - VOLTAGE GRADIENT CHARACTERISTICS OF COMPOUND *C*, PLOTTED WITH LOGARITHMIC COORDINATES

With the exception of the graphs at 65 and 80 deg C for compound *C*, the logarithmic power graph for each of these three compounds is a single straight line at every temperature; at these two temperatures, for compound *C*, each graph consists of two straight lines. Compound *C* contained rosin; it is well known that at temperatures at and above 65 deg C some of the constituents of rosin (abetic acid) volatilize and changes occur in its composition. This effect has been reported also by Whitehead (p. 57 in reference No. 10). The change in slope of these two graphs is undoubtedly due to some change in the rosin content of the compound. It is to be noted, however, that both sections of each graph are linear.

The foregoing graphs indicate that among cable impregnating compounds there is a tendency for the power loss to increase as a constant power of the voltage gradient. This exponential law has been observed by others.[11] Even at the two higher temperatures for compound *C* this law appears to hold. The constants of the functions at the higher values of voltage gradient, however, differ from those at the lower gradients.

The slopes ($\alpha$ in Table I) do not appear to have any definite relationship to the temperature. Above room temperature, slopes of less than 2.0 seem to predominate for compounds *A* and *C*, whereas the slopes for compound *B* are all greater than 2.0. When the slope is less than 2 the power factor decreases with increase in voltage gradient (see eq (4)). Whitehead, Kouwenhoven, and Hamburger[4] explain this phenomenon as follows: With the best impregnated paper, *i.e.*, absence of moisture, the ions become more mobile at the higher temperatures and accordingly are swept out of the field more rapidly by the increasing voltage gradients. Dunsheath[14] explains a rising power factor characteristic as being due to inevitable particles of moisture becoming more elongated under increasing voltage gradient.

From the foregoing relationships, it follows that the power loss per unit volume is

$$P = KE^{\alpha} \text{ watts per cu cm} \qquad (1)$$

where *K* is the loss coefficient, *E* the voltage gradient in volts per cm, and $\alpha$ the loss exponent. In Table I are given the values of $K$ and $\alpha$ for the three compounds, $A$, $B$ and $C$.

TABLE I

| Compound | Temperature deg C | $\alpha$ | $K$ (multiply by $10^{-13}$) |
|---|---|---|---|
| | 19.5 | 2.0 | 1.718 |
| | 35.0 | 2.15 | 0.915 |
| *A* | 50.0 | 1.9 | 18.9 |
| | 65.0 | 1.84 | 55.9 |
| | 80.0 | 1.875 | 98.5 |
| | 22.0 | 2.0 | 2.12 |
| | 35.0 | 2.45 | 0.0234 |
| *B* | 50.0 | 2.42 | 0.385 |
| | 65.0 | 2.05 | 3.95 |
| | 80.0 | 2.03 | 8.34 |
| | 24.0 | 2.0 | 3.34 |
| | 35.0 | 2.06 | 3.06 |
| | 50.0 | 1.95 | 17.7 |
| *C* | 65.0* | 1.98 | 37.7 |
| | 65.0† | 1.60 | 2,490.0 |
| | 80.0‡ | 1.95 | 73.5 |
| | 80.0§ | 1.42 | 23,800. |

*$E$ less than 66 kv per cm
†$E$ greater than 66 kv per cm
‡$E$ less than 64 kv per cm
§$E$ greater than 64 kv per cm

The foregoing power loss-voltage gradient characteristics are not unique properties of carefully prepared impregnated paper samples only. In Fig. 4 are shown the power loss-voltage gradient characteristics of a 10-ft sample of a 300,000-cir mil 6/32-in. (0.477-cm) wall impregnated-paper cable for several different temperatures. There are two sets of characteristics: one set was obtained before the cable had been subjected to any life test; the second set was obtained after this cable had been subjected to 190.7-hr life test, the temperature undergoing a weekly cyclic variation of from 20 to 60 deg C and the voltage undergoing a weekly cyclic variation of from 0 to 42.5 kv. Under these conditions this cable showed only very slight ionization. It is to be noted that in every case these characteristics are linear, indicating again that under these conditions the power loss varies as a constant power of the voltage gradient. Such characteristics are typical of many impregnated paper cables having no appreciable ionization.

It is believed that the coefficient $K$ and the exponent $\alpha$ may be used as a basis for the comparison of cable-impregnating compounds.

## POWER FACTOR CHARACTERISTICS

Equation (1) makes it possible to express the power factor of an impregnating compound in analytical form. Thus the power factor is given by

$$\text{Power factor} = \frac{P}{EI} = \frac{P}{E^2C\omega} = \frac{KE^\alpha}{E^2C\omega} \qquad (2)$$

where $C$ is the capacitance in farads per cu cm and $\omega$ is $2\pi$ times the frequency $f$.

From equation (2),

$$\text{Power factor} = \frac{KE^{\alpha-2}}{C\omega} \qquad (3)$$

It was found that the maximum variation of the capacitance $C$ at any one temperature was 4 per cent for all three compounds. This was an extreme value occurring at 50 deg C for compound $C$. For the most part, the variation was of the order of 1.5 per cent.

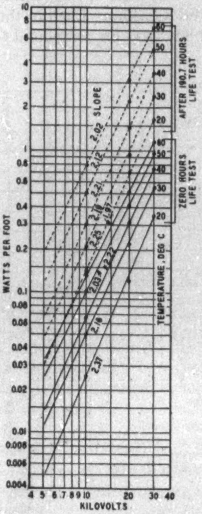
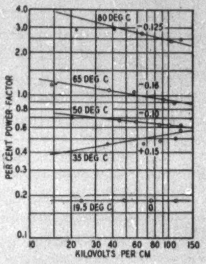


FIG. 4—(LEFT) POWER LOSS - VOLTAGE GRADIENT CHARACTERISTICS OF 300,000-CIR-MIL CABLE WITH 6/32-IN. IMPREGNATED PAPER INSULATION

FIG. 5—(BELOW) POWER FACTOR CHARACTERISTICS OF COMPOUND *A* PLOTTED WITH LOGARITHMIC COORDINATES



If an average value be used, at the most the change in the capacitance $C$ is only 2 per cent. Hence, for practical purposes

$$\text{Power factor} = K_pE^{\alpha-2} \qquad (4)$$

where $K_p$ is essentially a constant and equal to $K/C\omega$.

If the power factor characteristic be plotted with log-log coordinates, the resulting graph should be linear and the geometrical slope should be $\alpha - 2$. It is apparent that if $\alpha = 2$, the slope is zero and the characteristic is a horizontal straight line, such as occurs at room temperatures. If $\alpha > 2$, the slope is positive; if $\alpha < 2$, the slope is negative.

As an example, the log-log power factor characteristics for compound $A$ are shown in Fig. 5 and the slope of each characteristic is designated thereon. These characteristics are all linear. The slopes $(\alpha - 2)$ are very nearly in accordance with the values of $\alpha$ given in Table I.

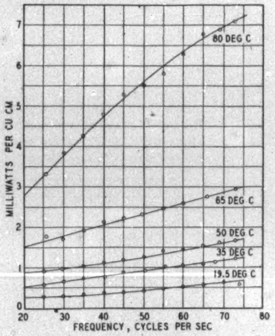
With each of the three compounds, the slopes of the power-factor characteristics for room temperature are all found to be zero in accordance with the foregoing analysis. With both compounds *A* and *C*, the slopes of the characteristics are both positive and negative.

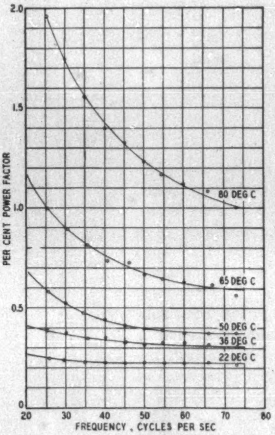
When the power factor characteristics are plotted on the usual coordinate paper, as a rule they are not exactly linear, but with the usual scales used they are nearly so. However, it is well known that their slopes are sometimes found to be positive and sometimes negative. Whether or not their slopes are positive or negative also depends on whether $\alpha$ is greater or less than 2. Frigon[11] also shows this last relationship. Each of the two characteristics at 65 and 80 deg C for compound *C* is found to have two slopes, which is in accordance with the changes in slope of the power characteristics in Fig. 3.

It may be observed that with a few of the characteristics, the relation of the plotted points to the characteristics indicates poor precision. This is due to the fact that the slopes are the differences of two nearly equal quantities $\alpha$ and 2 and hence the differences usually are very small, relatively to $\alpha$ and 2. As an extreme example, in Fig. 2 consider the characteristic at 80 deg C where $\alpha = 2.03$. An error of only 1 per cent in the value of $\alpha$ produces an error of 600 per cent in the slope of the power factor characteristic. Hence, these power factor characteristics are sensitive criteria of precision and the values of $\alpha$ in equation (1) may be obtained from them with much greater precision than from the power characteristics themselves.

## POWER-FREQUENCY CHARACTERISTICS

In electrical measurements over the limited ranges of power frequencies made with many different dielectrics, the authors have always found that if the dielectric was homogeneous, the power loss at constant temperature and frequency varied almost as a linear function of the frequency. This relationship has been found to hold with such high grade dielectrics as glass and pyrex,[6] with carefully impregnated paper insulation such as with the three compounds, *A*, *B*, and *C*, and even with cables which have negligible ionization. Frigon[11] in his tests of impregnated papers also shows this same relationship. (The authors realize that this linear relationship does not exist over extremely wide ranges of frequency because of the Debye dipole effect.[7,13])





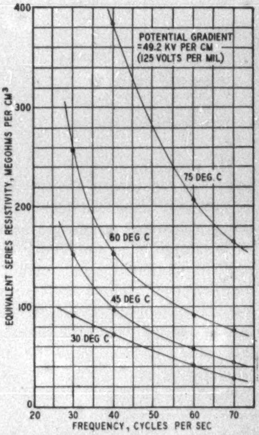


FIG. 6—(ABOVE) POWER LOSS-FREQUENCY CHARACTERISTICS FOR COMPOUND *A*

FIG. 7—(CENTER) POWER FACTOR-FREQUENCY CHARACTERISTICS FOR COMPOUND *B*

FIG. 8—(RIGHT) SERIES RESISTIVITY-FREQUENCY CHARACTERISTICS FOR COMPOUND *A*

The power-frequency characteristics for compound *A* at constant voltage gradient of 49.2 kv per cm (125 volts per mil) and for various temperatures, are given in Fig. 6; they are typical of those for the other two compounds. These characteristics are linear, except that the characteristic at 80 deg C shows very slight curvature. For most practical purposes, however, the linear relationship may be assumed and the power expressed by the equation

$$P = P_0 + mf \text{ watts per cu cm} \qquad (5)$$

where $P_0$ is the intercept of any characteristic with the power axis, $m$ is the slope of the characteristic and $f$ the frequency. Obviously $P_0$ is the inferred power loss per cu cm at zero frequency or with direct current.

In Table II are given the frequency constants $P_0$ and $m$ of the three compounds for different temperatures.

TABLE II

| Compound | Temperature deg C | $P_0$† | $m$† |
|---|---|---|---|
|  | 19.5 | 0.1 | 0.0075 |
|  | 35 | 0.25 | 0.017 |
| *A* | 50 | 0.55 | 0.0094 |
|  | 65 | 1.0 | 0.026 |
|  | 80 | 1.2* | 0.086* |
|  | 22 | 0.04 | 0.0075 |
|  | 36 | 0.14 | 0.018 |
| *B* | 50 | 0.36 | 0.009 |
|  | 65 | 0.66* | 0.0146* |
|  | 80 | 1.63 | 0.0201 |
|  | 24 | 0.15 | 0.0091 |
| *C* | 42 | 0.05 | 0.025 |
|  | 60 | 2.3 | 0.032 |
|  | 80 | 2.3 | 0.0725 |

*Up to about 60 or 65 cycles.

†Multiply all values by $10^{-3}$.

## POWER FACTOR-FREQUENCY CHARACTERISTICS

From equation (5), it may be shown that the power factor-frequency characteristics for such compounds are essentially rectangular hyperbolas.

For example, the power factor

$$\text{Power factor} = \frac{P}{E^2C\omega} = \frac{P_0 + mf}{E^2C(2\pi f)}$$

$$= \frac{P_0}{2\pi E^2Cf} + \frac{m}{2\pi E^2C} = \frac{a}{f} + b \qquad (6)$$

where $a$ and $b$ are essentially constant.

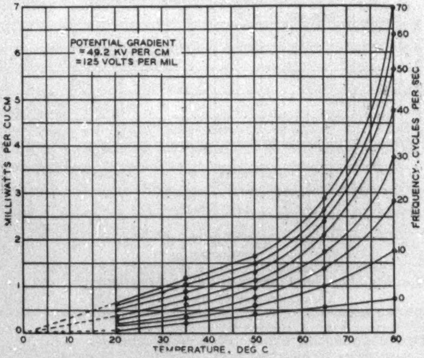


FIG. 9—POWER LOSS-TEMPERATURE CHARACTERISTICS FOR COMPOUND *A* AT DIFFERENT FREQUENCIES

The first term of equation (6) is the well-known equation of the rectangular hyperbola; the second term is constant. Hence, equation (6) represents a rectangular hyperbola in the first quadrant with the power axis as one asymptote and a line parallel to the frequency axis, + $b$ watts from it, as the other asymptote. Fig. 7 gives the power factor-frequency characteristics for compound $B$ at a constant voltage gradient of 49.2 kv per cm, (125 volts per mil) for different temperatures. It may be observed that these characteristics are rectangular hyperbolas in accordance with equation (6). (Corresponding characteristics for compounds $A$ and $C$ are very similar.) Frigon[11] shows this same type of characteristic, but does not attempt to derive the functions.

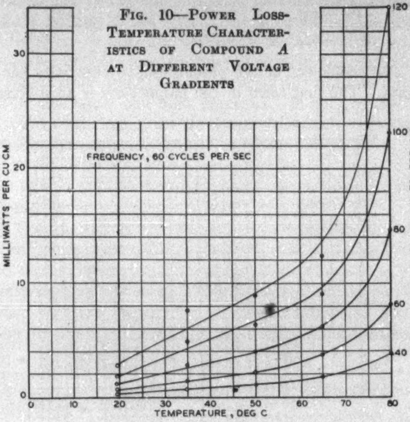


FIG. 10—POWER LOSS-TEMPERATURE CHARACTERISTICS OF COMPOUND *A* AT DIFFERENT VOLTAGE GRADIENTS

From equation (6) the power factor approaches $b$, or $m/(2\pi E^2C)$, as the frequency is increased, provided the dipole molecular effect does not occur. With compound $B$ at 65 deg C, $a = 0.1635$ and $b = 0.00363$. At a frequency of 50 cycles, the power factor is equal to $0.00327 + 0.00363 = 0.00690$.

Hence, at this temperature and frequency, the two terms in equation (6) are almost equal.

## EQUIVALENT SERIES RESISTIVITY

The equivalent series resistivity is

$$\rho = \frac{P}{I^2} = \frac{P}{E^2C^2\omega^2} \qquad (7)$$

When it is desired that $\rho$ become a function of the voltage gradient $E$, at constant temperature and frequency, equation (1) may be substituted in equation (7) giving

$$\rho = \frac{KE^{\alpha}}{E^2C^2\omega^2} = \frac{K}{C^2\omega^2}E^{\alpha - 2} \qquad (8)$$

Since $C$ is essentially constant for any given temperature and over the usual ranges of voltage gradient, equation (8) is the same form of function as the power factor characteristic. It is generally true that the equivalent series resistivity and the power factor characteristic are similar in form as already has been shown by one of the authors.[8]

When $\rho$ becomes a function of temperature, at constant frequency and voltage gradient, the function is essentially that of the power-temperature characteristic. When $\rho$ becomes a function of frequency, at constant voltage gradient and temperature, the function is a combination of a rectangular hyperbola and an inverse square function. For example, from equations (5) and (7)

$$\rho = \frac{P_0 + mf}{E^2C^2(2\pi f)^2} = \frac{1}{(2\pi EC)^2}\left(\frac{P_0}{f^2} + \frac{m}{f}\right) \quad (9)$$

The coefficient of the parenthesis is essentially constant. The first term in the parenthesis is an inverse square term and the second term used alone gives the equation of a rectangular hyperbola. Hence, the equivalent series resistivity characteristic is the sum of an inverse square function and a rectangular hyperbola. A family of these characteristics for compound $A$ is shown in Fig. 8.

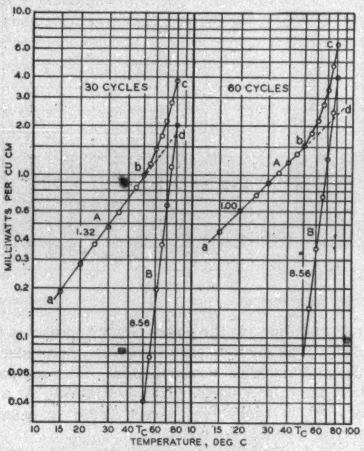


FIG. 11—POWER LOSS-TEMPERATURE CHARACTERISTICS OF COMPOUND *A*, PLOTTED WITH LOGARITHMIC COORDINATES

## EQUIVALENT PARALLEL CONDUCTIVITY

The equivalent parallel conductivity is

$$\gamma_p = \frac{P}{E^2} = \frac{KE^{\alpha}}{E^2} = KE^{\alpha - 2} \quad (10)$$

Hence, the equivalent parallel conductivity function is of the same form as the power factor function given in equation (4).[8] From equation (5), $\gamma_p$ as a function of frequency, with constant temperature and voltage gradient, is linear being similar to the power-frequency function.

## POWER-TEMPERATURE CHARACTERISTICS

It was found possible to resolve the power-temperature characteristics into two simple exponential components. This analysis is found to be valid for the family of characteristics plotted with constant voltage gradient, but with different values of frequency (Fig. 9). Except for the very lowest portions of the characteristics for compound $C$, the analysis is valid for the family of characteristics plotted with constant frequency and with different values of voltage gradient (Fig. 10).

Consider Fig. 11, which gives the power-temperature characteristics *abc* at both 30 and 60 cycles for compound $A$ (from Fig. 10) plotted with log-log coordinates. Up to 50 deg C each characteristic is linear, showing that up to this temperature the power increases as a constant power of the temperature. At 50 deg C, the upper portion *bc* of the graph departs from the lower linear portion *ab* and lies above *bd*, the lower linear portion extended. At temperature $T_c$, corresponding to point *b*, the characteristic departs from the simple initial exponential law. However, if the portion *bd* be subtracted from the portion *bc* and replotted on log-log coordinates, as shown by characteristic $B$, the resulting graph also is found to be linear. Thus, beyond the critical temperature $T_c$, the power is represented by the sum of two exponential characteristics $A$ and $B$. The geometrical slope and hence the exponent of the function is denoted on each characteristic. The characteristics shown in Fig. 11 are re-plotted in Cartesian coordinates in Fig. 12.

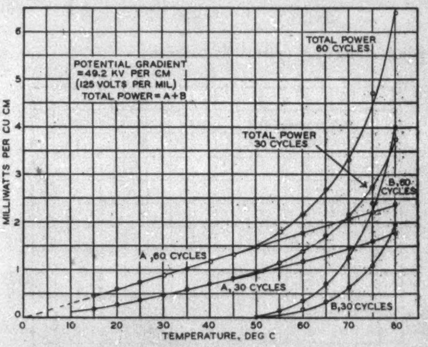


FIG. 12—COMPONENTS OF POWER LOSS-TEMPERATURE CHARACTERISTICS OF COMPOUND *A*

The total power $P$ may be expressed as the sum of two components

$$P = A + B \quad \textbf{(11a)}$$

$$= aT^n + bT^p \quad \textbf{(11b)}$$

where $a$ and $b$ are coefficients and $n$ and $p$ are exponents, all constant at any one frequency and voltage gradient;

the second terms are zero below the critical temperature $T_c$. The exponent *n* is of the order of unity and decreases with increase in frequency. The constant *a*, when used in connection with watts per cubic centimeter, varies from nearly zero at 20 cycles to the order of 0.05 to 0.1 at 70 cycles for compounds *A* and *B*; for compound *C*, *n* is of the order of from 2 to 4 and *a* varies from zero to 8 x $10^{-4}$. The variation of these two constants with frequency for all three compounds is shown in Fig. 13.

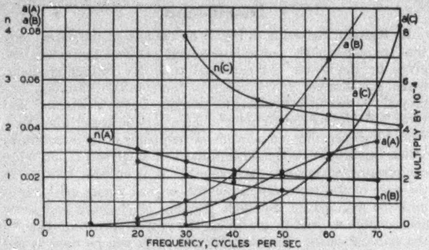


FIG. 13—VALUES OF *a* AND *n* OF EQUATION (**11b**) FOR ALL THREE COMPOUNDS

For compound *C* at the lower frequencies, the component *B* becomes negative. In Fig. 14 are shown three log-log power-temperature characteristics of compound *C* for 60, 45, and 30 cycles at a constant voltage gradient of 49.2 kv per cm (125 volts per mil). It may be noted that at 60 cycles the portion *bc* of the characteristic lies above the straight line *abd*; at 45 cycles there is no deviation from a straight line relationship, showing that the *B* component is zero at all temperatures; at 30 cycles the portion *bc* of the characteristic lies below the straight line *abd*, showing that the *B* component of the power characteristic is negative. However, at both 60 and 30 cycles the *B* component of the power loss still follows the simple exponential law, as is shown by the characteristic *B* for both these frequencies.

The values of the constants *b* and *p* for the three compounds are given in Table III.

TABLE III—CONSTANTS *b* AND *p* IN EQUATION (11b)

| Frequency cycles per sec | Compound *A* | | Compound *B* | | Compound *C* | |
|---|---|---|---|---|---|---|
| | *b* | *p* | *b* | *p* | *b* | *p* |
| 75 | | | | | 0.542x$10^{-9}$ | 5.08 |
| 70 | 0.222x$10^{-15}$ | 8.56 | 0.096x$10^{-12}$ | 7.0 | | |
| 60 | 0.198x$10^{-15}$ | 8.56 | 9.89 x$10^{-12}$ | 5.88 | 0.704x$10^{-8}$ | 4.38 |
| 50 | 0.198x$10^{-15}$ | 8.56 | 4.95 x$10^{-12}$ | 6.04 | | |
| 40 | 24.07 x$10^{-15}$ | 7.40 | 0.425x$10^{-12}$ | 6.54 | | |
| 30 | 0.103x$10^{-15}$ | 8.56 | 0.211x$10^{-16}$ | 8.84 | 0.502x$10^{-15}$ | 8.50 |
| 20 | 13.58 x$10^{-15}$ | 7.32 | | | | |
| 10 | 0.019x$10^{-15}$ | 8.60 | | | | |

It is interesting to note that Frigon[11] also expressed portions of his power-temperature characteristic as two logarithmic functions. However, his characteristics were of the U or V type. He gives the power *P* as follows:

$$\text{From } 0 \text{ deg C to } 25 \text{ deg C} \quad P = mT^{-0.3}$$
$$70 \text{ deg C to } 110 \text{ deg C} \quad P = oT^{3.6}$$

where *P* is power, *m* and *o* constants, and *T* temperature in deg C.

The first term applies to the portion of the characteristic at the left of the minimum and the second term to the portion at the right of the minimum. It is also interesting to note the similarity of the content and analyses of this paper to those of Frigon, although the Frigon paper was not discovered by the authors until after this paper had been prepared. It may be noted further that none of the three samples described in this paper shows any tendency toward the well known U or V power or power factor characteristics. This may well be due in part to the dielectric characteristics of the paper itself.

The analysis of the power loss in these compounds into two exponential components appears at this time to be only empirical. However, two factors seem to have some significance: First, the critical change occurs at or very near 50 deg C; other investigators have found this temperature to be critical in relation to the electrical characteristics of compounds of this character. Second, the power losses, whether functions of voltage gradient or of temperature, have a tendency to follow an exponential law. It is well known that ionization currents in gases, for example, such as are given by Townsend's continuity theorem, are exponential in character. Hence, it may be shown at some later time that the foregoing relationships are due to inherent characteristics of the molecular relationships within the dielectric.

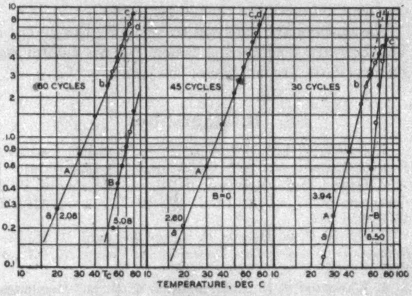


FIG. 14—POWER LOSS-TEMPERATURE CHARACTERISTICS OF COMPOUND *C* FOR THREE DIFFERENT FREQUENCIES, PLOTTED WITH LOGARITHMIC COORDINATES

**Potential gradient, 49.2 kv per cm (125 volts per mil)**

## CONCLUSIONS

1. An abrupt change in the slope of the cooling curves of some cable compounds occurs in the neighborhood of 50 deg C; this may indicate changes in the molecular structure.

2. It appears to be a general law that the power loss in cable compounds varies as a constant exponential power of the voltage gradient, the exponent usually being 2 at room temperature; at higher temperatures it may be greater or less than 2.

3. The power factor characteristics of cable compounds are exponential functions of the voltage gradient, the exponent being related to that for the power characteristics.

4. The power-frequency characteristics are essentially linear, having a positive intercept at zero frequency.

5. The power factor-frequency characteristics are essentially rectangular hyperbolas.

6. The equivalent series resistivity-voltage gradient characteristic is the same type of function as the power factor-voltage gradient characteristic.

7. The equivalent parallel conductivity-voltage gradient characteristic is the same type of function as the power factor-voltage gradient characteristic.

8. The power-temperature characteristics for constant frequency and constant voltage gradient appear to consist of two terms, each of which is a constant-exponential function of the temperature.

The authors are indebted to Dean H. E. Clifford of The Harvard Engineering School for his helpful suggestions in the preparation of this paper.

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## Discussion

**R. Reiter:** Referring to Fig. 2, or Table I, of the paper, note that the slopes of the power loss-voltage gradient characteristics, given by the power loss exponent $\alpha$ of the voltage gradient, reach a maximum in the range of temperature variation employed. Other investigators, for example Debye*, Kitchin,* and Race, have found similar critical characteristic peaks when they varied the operating temperature or frequency of their materials, which consisted of single chemicals such as glycerin, and more complicated compounds such as oils. It is possible that, as in the case of the turbo-alternator set, critical points exist which must be avoided by the cable designer in choosing and using cable materials, and in specifying the proper operating range of the finished cable. Professor Dawes' work can be used to advantage in determining the proper design constants and thus can reduce materially the factor of ignorance which is now known to be high.

**Eric A. Walker:** The writer recently has been conducting numerous tests at the Harvard Engineering School, to determine the relationship between the electrical characteristics of cables and the frequency. It was found that the power loss in impregnated paper insulated cables was given by the function.

$$P = P_0 + mf^{\alpha} \tag{1}$$

where

$P$ is the a-c power loss in watts per 1,000 ft.

$P_0$ is the d-c power loss in watts per 1,000 ft.

$m$ is a constant for any one voltage and temperature.

$f$ is the frequency in cycles per second.

$\alpha$ is a constant exponent for any one voltage and temperature.

Then the

$$\text{power factor} = \frac{P_0}{Kf} + \frac{m}{Kf^{1-\alpha}} \tag{2}$$

where $K = 2\pi E^2 C$

$E$ being the impressed rms voltage.

$C$ the capacitance in farads.

If $\alpha$ = unity these equations are identical to those given by Professor Dawes, and equation (2) represents a rectangular hyperbola with one asymptote displaced from the frequency axis by a constant quantity.

$P_0$ was measured accurately by applying a high continuous voltage and measuring the steady-state leakage current. The power loss $P$ with alternating voltage was measured with a Dawes-Hoover bridge.

For a 350,000 cir-mil stranded conductor cable with 19/64 inch (7.52 mm) wall impregnated paper insulation, at 13,950 volts and room temperature, $P_0$ was found to be 0.0014 watt per 1,000 ft and $P$ at 60 cycles per second was 24.2 watts per 1,000 ft.

However, as is shown in Fig. 1, curve $A$, $\alpha$ was not equal to unity but equal to 0.965. By inspecting equation (2) it is seen that the power factor-frequency characteristic is not a rectangular hyperbola but is a characteristic which rises more rapidly than a rectangular hyperbola as the frequency decreases. This function is shown in Fig. 2.

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*This work is described in Gemant's "Electrophysik der Isolierstoffe."

It is evident also that if $\alpha$ were greater than unity the power factor might decrease as the frequency is decreased, for then we have

$$\text{power factor} = \frac{P_0}{Kf} + mf^{\alpha-1} \qquad (3)$$

as is shown from the d-c measurements $mf^{\alpha}$ greatly exceeds $P_0$ and as $mf^{\alpha-1}$ will decrease with frequency for values of $\alpha$ from 1 to 2, the power factor also may decrease.

The equivalent series resistance as determined by Professor Dawes is given by:

$$\rho = \frac{P}{K'f^2} = \frac{P_0}{K'f^2} + \frac{m}{K'f^{2-\alpha}} \qquad (4)$$

where $K' = (2\pi EC)^2$

If, as has been shown $P_0$ is negligible compared with $mf^{\alpha}$, and $\alpha$ equals unity the equation represents a rectangular hyperbola. However as $\alpha$ in the cable under discussion equals 0.965 the characteristic rises more rapidly than a rectangular hyperbola as the frequency is decreased. In Fig. 2 the equivalent series resistance characteristic for this cable rises more rapidly than a rectangular hyperbola.

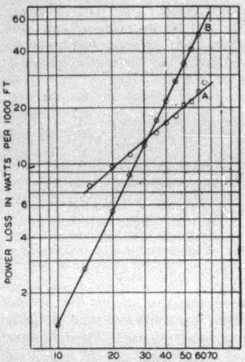

Fig. 1—Power Loss *vs* Frequency

Curve A—350,000-cir mil stranded conductor 19/64 in. wall impregnated paper insulation—13,950 volts, 20 deg 5 C

Curve B—No. 6 solid conductor 7/32 in. wall rubber insulation—7,000 volts, 20 deg 5 C

Very different characteristics were obtained when rubber-insulated cables were tested. For a No. 6 solid copper conductor, 7/32 inch (5.55 mm) wall rubber insulation at room temperature and 7,000 volts the power factor is a linear function of frequency from 10 to 60 cycles per sec. The characteristic for frequencies from 10 to 60 cycles is given in Fig. 3. By extrapolation the power factor at zero frequency becomes zero. This seems anomalous for under continuous voltage conditions, after the transient has subsided, the power factor equals unity. However the definition of the power factor as the cosine of the angle between the voltage and current loses its significance with continuous voltage.

The equivalent series resistance and the equivalent series capacitance remain constant with change of frequency.

With an equivalent series circuit to represent the dielectric:

$$\text{power} = \frac{KE^2\,(\text{power factor})^2}{\text{equivalent series resistance}} \qquad (4)$$

Therefore the power should be an exponential function of frequency. This is shown by curve *B* in Fig. 1 where power is plotted as a function of frequency on log-log coordinate paper. The slope of the characteristic is 2. Therefore for this rubber insulated cable

$$P = P_0 + bf^2$$

where $P_0$ at 7,000 volts and room temperature = 0.0077 watts/1,000 ft and is negligible above 10 cycles per second; $b$ is a constant and is equal to $2.83 \cdot 10^{-10}E^2$.

**J. B. Whitehead:** Most of the behavior shown for impregnated paper by Messrs. Dawes and Humphries can be accounted for in terms of the theory of dielectric absorption. Under this theory power loss increases as the square of the voltage gradient. At higher temperatures the increase in the conductivity of the oil causes a more rapid rise with voltage. At low temperatures power factor is independent of the voltage gradient and either may rise or fall at higher temperatures, depending on the initial conductivity or ionic content of the oil. Power loss is proportional to frequency, but also proportional to power factor, and the latter either may rise or fall with frequency. Consequently, the power frequency relationship is not simple. In the writer's

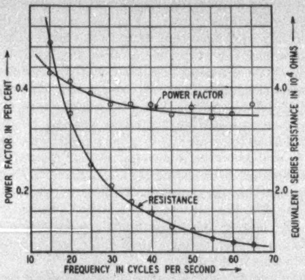

Fig. 2—Power Factor and Equivalent Series Resistance *vs* Frequency

350,000-cir mil stranded conductor 19/64 in. impregnated paper insulation—13,950 volts, 20 deg 5 C

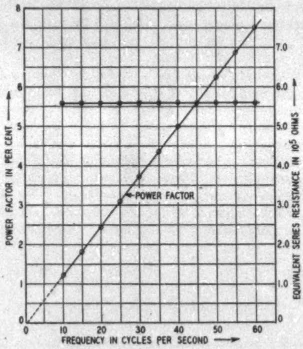

Fig. 3—Power Factor and Equivalent Series Resistance *vs* Frequency

No. 6 solid conductor—7/32 in. wall rubber insulation—7,000 volts, 20 deg 5 C opinion, the power factor frequency curve is not a hyperbola, but the curves as the authors have shown them, if extended to lower frequencies, would pass through a maximum decreasing to zero at zero frequency. A number of variations in the shape of the loss temperature curve of impregnated paper, as affected by the characteristics of the oil, may be seen in the paper, *The Dielectric Losses in Impregnated Paper*, A.I.E.E. TRANS., June 1933, p. 667.

**C. L. Dawes:** Mr. Walker finds that with a commercial impregnated paper cable the alternating current component of power loss does not increase proportionately to the frequency as was found by the authors for carefully impregnated flat samples, but rather to the 0.965 power. The two exponents differ from each other only by 3.5 per cent which is not large when the wide variations among the properties of even similar dielectrics are considered. The difference cannot be attributed to errors in measurement since the precision was far too high to permit a deviation of 3.5 per cent. It can be shown theoretically that with homogeneous insulation the power loss as a function of frequency should be the same whether the sample is flat or cylindrical. As is well known a somewhat similar discrepancy exists between the actual dielectric strength of homogeneous cylindrical dielectrics, and that derived theoretically from the properties of flat samples. Mr. Walker who is conducting this research at the Harvard Engineering School continually is obtaining new data and eventually it may become possible for him to reconcile this difference in the exponents.

It is this same difference in the exponents which accounts for the power factor and equivalent series resistance relationships which he derives from his equations (3) and (4).

Mr. Walker is obtaining some very interesting results with rubber cables when subjected to relatively high voltage gradients. The alternating current component of power loss appears to increase as the square of the frequency rather than as the first power as is found with impregnated paper. This relationship is quite surprising. Mr. Walker intends to investigate this phenomenon further and undoubtedly will conduct power frequency experiments with flat rubber samples for comparison.

Doctor Whitehead states that at the higher temperatures the increase in the conductivity of the oil causes a more rapid rise of loss with the voltage gradient than at the lower temperatures. From his previous sentence which refers to the square of the voltage gradient it might be inferred that at the higher temperatures the loss increased at a higher power of the voltage gradient than the squared power. That this is not true is shown in Table I. For example, with compound *A* the value of the exponent $\alpha$ at 19.5 deg C is 2.0 whereas at 80 deg C it is but 1.875. Likewise the exponent for compound *C* at the higher temperatures is considerably less than at room temperature. The exponent for compound *B* reaches a maximum of 2.4 at 50 deg C and is only 2.03 at 80 deg C. Similar relationships occur with the 300,000 cir mil cable whose characteristics are shown in Fig. 4. Hence the more rapid rise of loss with voltage gradient at the higher temperatures to which Doctor Whitehead calls attention and which undoubtedly is due in a large measure to an increase in the conductivity of the oil obviously is not given by an increase in the voltage gradient exponent. Further inspection of Table I shows however that the coefficient *K* increases very rapidly with temperature. For example, with compound *A* the value of *K* at 80 deg C is 98.5 compared with 1.718 at 19.5 deg C. Thus the more rapid increase in loss with voltage gradient at the higher temperatures is accounted for by an increase in the power loss coefficient and not in the voltage gradient exponent.

Doctor Whitehead's statement that power loss is proportional to power factor obviously is correct, but in attempting to analyze the properties of dielectrics we find it more simple to consider power loss as a fundamental property of the dielectric rather than the power factor. The power factor is a function of two properties, power loss and voltamperes, and the voltamperes in turn are proportional to the permittivity. The permittivity obviously is a fundamental property of the dielectric. Hence to us it appears more rational to consider power loss rather than power factor as a fundamental criterion of dielectric properties.

It may well be, as Doctor Whitehead states, that the power factor frequency characteristics are not rectangular hyperbolas to frequencies at or very near zero since the power factor may be zero at zero frequency. We of course find the characteristics to be rectangular hyperbolas in the frequency range of from 75 to 20 cycles. The region between zero frequency and the very low power frequencies is practically unexplored. The experimental difficulties in extending the frequency below 15 cycles are well known. To us it would seem that the characteristics would remain rectangular hyperbolas at least to frequencies that were almost zero. Possibly near zero frequency a maximum might be reached and the power factor fall very rapidly to zero, thus giving a discontinuity in the slope of the characteristic at or near zero frequency. However, so far as we know this fact has not been confirmed experimentally. Mr. Walker states that with rubber cables the power factor function does give zero power factor at zero frequency. Our knowledge of the fundamental properties of dielectrics would be increased considerably were data on the properties of dielectrics between zero frequency and 15 cycles available, particularly data near zero frequency. The difficulties of making these measurements may be overcome at some time in the near future if the recent progress in making dielectric loss measurements continues.

# Loss Characteristics of Silicon Steel at 60 Cycles with D-C Excitation

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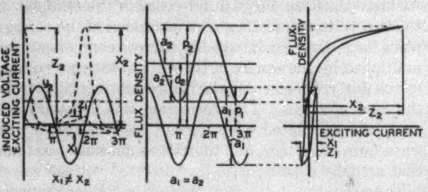
Associate, A.I.E.E.

INTEREST in the loss characteristics of sheet steel subjected to combined alternating and direct magnetic fields is of long standing. Previous work on the subject includes that reported by M. Rosenbaum[1] and F. Holm[2] in 1912, by J. D. Ball[3], and L. W. Chubb and Thomas Spooner [4,5] in 1915 and '21, and by Y. Niwa, Y. Asami[6], J. Matura, and J. Sugiura[7] in 1923 and '24. (For numbered references see Bibliography.)



A
INDUCED VOLTAGE (—)
EXCITING CURRENT (---)

B
FLUX DENSITY

C
HYSTERESIS LOOPS

FIG. 1—WAVE FORMS OF INDUCED VOLTAGE, FLUX DENSITY, AND EXCITING CURRENT WITH CORRESPONDING HYSTERESIS LOOPS, SHOWING THE EFFECT OF D-C EXCITATION

$a$—Alternating flux density (one-half total pulsation)
$d$—Direct flux density (average over a complete cycle)
$p$—Peak flux density (maximum in each cycle)
$x$—Amplitude of exciting-current pulsation
$y$—Direct component of exciting current (average current)
$z$—Peak value of exciting current
Subscript 1 refers to conditions with no d-c excitation
Subscript 2 refers to conditions with d-c excitation

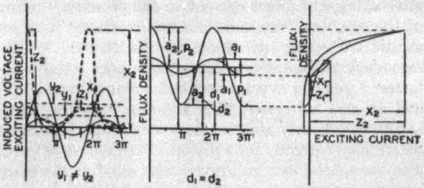
There are a number of applications in which either power transformers or instrument transformers may be subjected to d-c excitation. The a-c core-loss and excitation characteristics of the core material under such conditions are of importance, for they affect the rating of the power transformers and the accuracy of the instrument transformers. Combined alternating and direct magnetic fields are present in other types of apparatus also, affecting their performance by changing the characteristics of the magnetic circuits.

The diagrams of Fig. 1 illustrate the change of the cycle of magnetization which is caused by a direct component of exciting current. The flux wave and the corresponding hysteresis loop are shifted from their symmetrical positions by a direct component of flux density. The shape of the hysteresis loop is changed; in general, its area, which represents the hysteresis loss per cycle, also is changed, although the amplitude of pulsation (vertical length) remains the same.

The eddy current loss, being a function of the effective value of the induced voltage, is not affected by the direct component of flux density, if, as assumed in Fig. 1, the amplitude and form of the flux and voltage waves remain unchanged. The assumption regarding the form of the voltage wave is only approximately correct, however. Changes in the exciting current wave form and amplitude will react upon the impedance in the magnetizing circuit to distort the wave form of the induced voltage; so that the eddy current loss will be changed somewhat.

The change in the exciting current is associated with the change in the shape of the hysteresis loop. The general slope of the loop is decreased, so that the same pulsation of flux density (vertical length) requires a much greater pulsation of exciting current (horizontal length). Thus, in Fig. 1, the amplitude of the exciting current pulsation ($x_2$, $x_1$) is much greater for the displaced than for the symmetrical flux wave, although the amplitude of flux pulsation ($a_2$, $a_1$) is the same for both. There is, of course, a small component of exciting current due to eddy current loss, which is neglected in Fig. 1.

The converse effect, that of superposed a-c excitation on the d-c excitation is illustrated by the diagrams of Fig. 2. The two flux waves have the same direct components of flux density ($d_1$, $d_2$) but different alternating components ($a_1$, $a_2$). The direct components of exciting current ($y_1$, $y_2$) are quite different.



A
INDUCED VOLTAGE (—)
EXCITING CURRENT (---)

B
FLUX DENSITY

C
HYSTERESIS LOOPS

FIG. 2—WAVE FORMS OF INDUCED VOLTAGE, FLUX DENSITY, AND EXCITING CURRENT, WITH CORRESPONDING HYSTERESIS LOOPS, SHOWING THE EFFECT OF VARYING FLUX PULSATION ON THE DIRECT COMPONENT OF EXCITATION

$a$, $d$, $p$, $x$, $y$, $z$—Same as in Fig. 1
Subscript 1 refers to conditions with a small flux pulsation
Subscript 2 refers to conditions with a large flux pulsation

The changes in the shape of the hysteresis loop illustrated in Figs. 1 and 2, have been shown in detail by several of the investigators mentioned previously. This paper describes a series of a-c core loss and excitation tests with superposed d-c excitation which recently were made on low-, medium-, and high-silicon sheet steel, and presents in detail the results for the first and the third of these three grades.

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*Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10-12, 1933.*

### METHODS OF TEST

The tests were made on 20-lb laminated ring samples 9.45 in. outside diameter by 6.3 in. inside diameter. The rings were wound with uniformly distributed primary and secondary windings of 200 turns each, the primary being outside of the secondary.

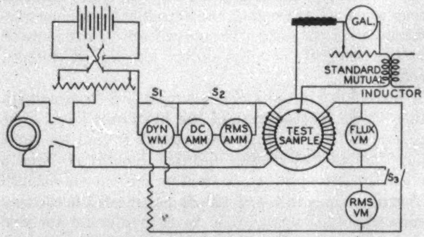


FIG. 3—CIRCUIT DIAGRAM FOR CORE LOSS AND EXCITATION TESTS WITH SUPERPOSED D-C EXCITATION

Core loss—$S_1$ open: $S_2$, $S_3$ closed
Excitation—$S_1$ closed: $S_2$, $S_3$ open

Fig. 3 shows the apparatus and circuits used, and makes clear the method of supplying the combined alternating and direct current to the primary winding of the sample. The core loss was measured with an astatic reflecting dynamometer wattmeter. The secondary voltage was measured with both a flux voltmeter[8,9] (reading average rectified voltage times 1.111) and an rms voltmeter, thus allowing both the alternating flux density and the secondary copper loss to be determined correctly for a distorted voltage wave form. The use of the two voltmeters also allowed the eddy current loss to be corrected for a distorted voltage wave form, in separating the two components of the total core loss.

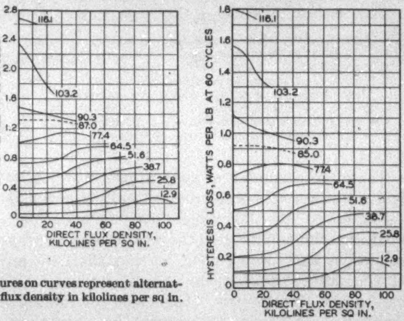
The direct flux density was measured with an overdamped ballistic galvanometer connected to a single-turn coil on the sample, deflections being read as the direct current was reversed. Several reversals were made each time before recording the deflection. A high-reactance choke coil was connected in series with the galvanometer to insure a negligible alternating current and negligible loss in that circuit. The galvanometer was calibrated by means of a standard mutual inductor, its sensitivity being adjusted by a shunt resistance.

In making the tests, the flux voltmeter reading, and consequently the alternating flux density, was held constant at each desired value while the direct current was varied in steps over as great a range as the current carrying capacity of the primary winding permitted. The sample was demagnetized each time before proceeding to the next value of alternating flux density. Considerable time was allowed between readings with no power on, in order to minimize heating of the sample, and consequent error in the calculation of the eddy current loss.

In separating the total core loss into hysteresis and eddy current components, the percentage of eddy current loss with no d-c excitation was taken from the results of numerous separation tests previously made on the same material, and it was assumed that the eddy current loss was not affected by superposed d-c excitation except as the voltage wave form was changed. At high densities, where a difference in the readings of the two voltmeters indicated a distortion of the voltage wave form, the calculated eddy current component was multiplied by the square of the ratio of the rms voltage to the flux voltmeter voltage before subtracting it from the total core loss. This correction was necessary because the calculated eddy current loss was for a sine wave form of voltage, and therefore somewhat less than that actually existing with the distorted voltage wave.

The excitation tests were made in a similar manner, except that the total rms current and the direct current were measured, instead of the power in watts. An rms ammeter and a d-c ammeter were connected in series with the primary winding, and the wattmeter and the rms voltmeter were switched out of the circuit. The a-c component of exciting current was determined from the equation

$$I_{a-c} = \sqrt{I_{total}^2 - I_{d-c}^2}$$



Figures on curves represent alternating flux density in kilolines per sq in.

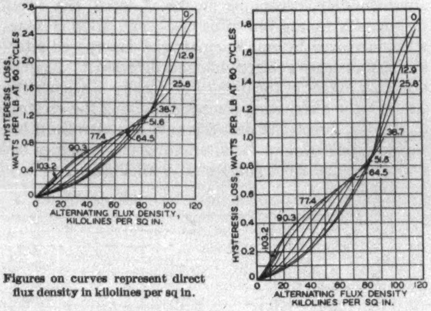
FIGS. 4 AND 5.—HYSTERESIS LOSS *vs.* DIRECT FLUX DENSITY WITH VARIOUS ALTERNATING FLUX DENSITIES, FOR LOW-SILICON STEEL (LEFT) AND (RIGHT) FOR HIGH-SILICON STEEL

### RESULTS

The silicon contents were approximately 2½, 3¼, and 4 per cent for the low-, medium-, and high-silicon steels, respectively. Each material was annealed before the samples were punched out. The low-silicon steel sample was punched from sheets 0.019 in. thick; the medium- and high-silicon steel samples were punched from sheets 0.014 in. thick.

Results are presented graphically in Figs. 4 to 11 inclusive. Only the hysteresis component of core loss is given. Alternating flux density values refer to half the amplitude of flux pulsation, and direct flux density values to the average flux density over a complete cycle; a-c excitation values refer to the effective value of the alternating component and d-c excitation values to the average current over a complete cycle.

The alternating flux density ranged from zero to 18,000 gausses (116.1 kilolines per sq in.), and the direct flux density from zero to 15,600 gausses (100 kilolines per sq in.) the highest value of the sum of the two components being approximately 20,000 gausses (129 kilolines per sq in.).



Figures on curves represent direct flux density in kilolines per sq in.

Figs. 6 and 7—Hysteresis Loss *vs.* Alternating Flux Density with Various Direct Flux Densities, for Low-Silicon Steel (Left) and (Right) for High-Silicon Steel

Throughout the range of flux density for which the solid-line a-c excitation curves of Figs. 8 and 9 are plotted, the form factor of the induced voltage did not vary from 1.111 by more than 1 per cent. For the dotted-line curves of Figs. 8 and 9, with the exception of the two uppermost curves, the form factor of the induced voltage wave did not vary from 1.111 by more than 4 per cent, and for the two uppermost dotted-line curves it did not vary from 1.111 by more than 9 per cent.

Curves for the medium-silicon steel (not included in the paper) were similar in form to those for the other two grades.

## Discussion of Results

*Hysteresis Loss.* Inspection of the curves of Figs. 4 and 5 shows that for alternating flux densities of 14,000 gausses (90.3 kilolines per sq in.) and greater, the hysteresis loss tends to decrease immediately as direct flux density is superposed; for alternating flux densities of 12,000 gausses (77.4 kilolines per sq in.) and less, it tends first to increase to a maximum, and then to decrease. For these lower densities, the hysteresis loss did not fall below the value without superposed direct flux density. However, the final slopes of some of the curves (Figs. 4 and 5) indicate that such a reduction might occur if the direct flux density were carried high enough.

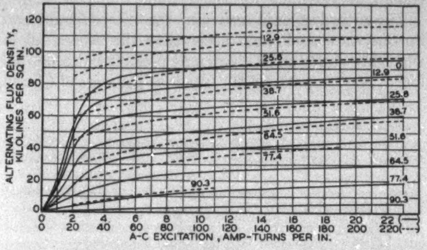


Fig. 8—Alternating Flux Density *vs.* A-C Excitation with Various Direct Flux Densities, for Low-Silicon Steel

Figures on curves represent direct flux density in kilolines per sq in.

In the range between the two densities given in the preceding paragraph, there is an alternating flux density for which the initial tendency of the hysteresis loss is neither to increase nor to decrease. It may be called the "critical" value. For the low-, medium- and high-silicon steels the critical values are approximately 13,500, 13,800 and 13,200 gausses (87, 89, 85 kilolines per sq in.) respectively. Two of these are illustrated by the dotted-line curves in Figs. 4 and 5. Values for the dotted-line curves were read from the curves of Figs. 6 and 7, the critical alternating flux density being approximately the density at which the curve for no direct flux density intersects that for 2,000 gausses (12.9 kilolines per sq in.).

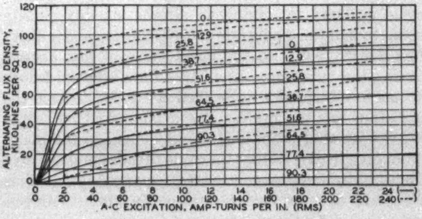


Fig. 9—Alternating Flux Density *vs.* A-C Excitation with Various Direct Flux Densities, for High-Silicon Steel

Figures on curves represent direct flux density in kilolines per sq in.

Table 4 of Doctor Holm's paper[2] shows a critical value of 13,450 gausses (86.7 kilolines per sq in.) for motor sheet steel. Table I of the paper by Chubb and Spooner[4] indicates a critical value of approximately 10,300 gausses (66.5 kilolines per sq in.) for silicon steel. Apparently none of the other investigators referred to carried the alternating component of flux density high enough to determine the critical value.

The critical value indicated by the tests of Chubb and Spooner is considerably lower than the others, all of which are nearly alike. This may possibly be accounted for, at least in part, by the fact that the tests of Chubb and Spooner were made on a transformer rather than on a ring sample as were the present tests and those of Dr. Holm.

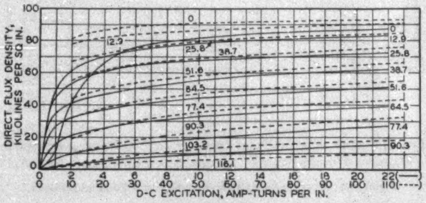


**Fig. 10—Direct Flux Density *vs.* D-C Excitation with Various Alternating Flux Densities, for Low-Silicon Steel**

**Figures on curves represent alternating flux density in kilolines per sq in.**

These results also may be used to calculate approximately the hysteresis loss which occurs when alternating flux waves of two different frequencies are combined to form a flux wave with pulsations. The loss for each cycle of the pulsation during one low frequency cycle is found by taking an alternating flux density equal to half the amplitude of the pulsation and a direct flux density equal to the mean value of flux density during the pulsation. The losses for all the pulsations in one low frequency cycle then are added to give the pulsation loss per cycle. The symmetrical hysteresis loss for an alternating flux density equal to the maximum flux density during the cycle then is added to give the total hysteresis loss per low frequency cycle. This procedure assumes that the area of the minor hysteresis loops traced by the pulsations of flux is approximately the same as that of the minor loops of the same flux density range which have been repeated many times with a constant displacement, and that the area is the same whether the upper tips of the minor loops be on the normal induction curve or on the boundary of a large symmetrical loop. The paper by Spooner[5] shows that these are approximately true, although the first minor loop is somewhat larger than succeeding ones, and the area varies slightly with horizontal displacement of the loop even though the vertical displacement is constant. The minor loops also may slightly affect the area of the symmetrical loop. Unfortunately, no data appear to be available to determine the extent of this effect.

*Excitation.* The first group of excitation curves (Figs. 8 and 9) shows that for any given alternating flux density, superposed d-c excitation increases the required a-c excitation. The solid-line curves of Figs. 8 and 9 represent the rms excitation corresponding to a sine wave of induced voltage, since for the range they cover, the form factor of the induced voltage was within 1 per cent of 1.111. The values of excitation given in the dotted-line curves, for which the wave form became somewhat distorted, are higher than would have been obtained with a sinusoidal voltage wave.

The second group of excitation curves (Figs. 10 and 11) shows the effect of superposed a-c excitation on the direct flux density and the d-c excitation. In the range from zero up to 11,200 gausses (72 kilolines per sq in.) approximately, depending on the material, the direct flux density for a given value of d-c excitation is somewhat increased by small amounts of superposed alternating flux density; larger amounts decrease it. Neither the exact extent of the direct flux density range nor the value of the alternating component giving the greatest increase of direct flux density could be determined because of lack of data for alternating flux densities between zero and 2,000 gausses (12.9 kilolines per sq in.) Direct flux densities above this range are not increased at all by superposed a-c excitation, but are immediately decreased.

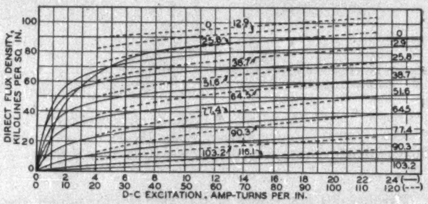


**Fig. 11—Direct Flux Density *vs.* D-C Excitation with Various Alternating Flux Densities, for High-Silicon Steel**

**Figures on curves represent alternating flux density in kilolines per sq in.**

## CONCLUSIONS

1. These tests constitute an addition to existing core loss and excitation data which will be helpful in designing apparatus in which combined alternating and direct magnetic fields occur. They will assist also in predicting the performance of existing designs when subjected to similar conditions of magnetization.

2. Both alternating and direct components of flux density were carried to high values. Corrections were

made for distortion of the voltage wave form at high densities.

3. In the range of alternating flux density below a certain value, which may be called the "critical" value, hysteresis loss tends first to rise, then to reach a maximum, and finally to decrease, as d-c excitation is superposed and the alternating component of flux density is held unchanged. Superposed d-c excitation decreases the hysteresis loss for any given alternating component of flux density in the range above the critical value.

4. The critical value of alternating flux density for silicon steel lies in the range 13,200 to 13,800 gausses (85 to 89 kilolines per sq in.).

5. The a-c excitation for any given alternating flux density is increased by superposed d-c excitation.

6. The d-c excitation for a given direct flux density in the low or moderate density range is decreased by a small amount of superposed a-c excitation, but is increased by larger amounts. The d-c excitation for a given direct flux density in the high-density range is increased by superposed a-c excitation.

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## Discussion

**S. L. Gokhale:** Most of the work on this subject has been conducted by engineers and along lines representing the engineer's point of view. All such work, including Mr. Edgar's contribution, has added greatly to our knowledge of facts regarding magnetic hysteresis. It must be recognized, however, that from the physicists point of view, we are yet very much in the dark. Fig. 1c in Mr. Edgar's paper, shows the forms of two hysteresis loops for the same range of flux change, one symmetrical and the other unsymmetrical. The latter is unsymmetrical not only in position but also in form; the ascending and descending sides of the loop are dissimilar. Why are they so? The unsymmetrical loops generally are larger than the symmetrical. Why? In some cases, this relation is reversed, the unsymmetrical loop being the smaller. Why? These and other cognate questions are still unanswered. The duty of seeking answers to these questions rests not on the engineers but on the physicists.

These questions suggest another much more fundamental question. Why is it, that we know so little about magnetism, although we know comparatively so much more about electricity, and although the two branches of physical science not only are related but also analogous? It seems as if some special obstacle to knowledge has developed on the magnetic side, without affecting the electrical side. Is there really such an obstacle, and if so what is it?

In 1852, Weber formulated his well-known theory of magnetic phenomena. He assumed, that a magnetic body is made up of molecular permanent magnets, and that the process of magnetization consists of orientation of these molecular magnets, under the directive influence of a magnetizing force, $H$. According to this theory, the magnetic flux density $B$ at any point, is a magnetic force of the same nature as $H$, with this difference, that $B$ is the resultant force of which $H$ merely is one component; the other component is the magnetic force emanating from the poles of the molecular magnets. This conception of $B$, leads to the conclusion that permeability is a non-dimensional quantity. This relationship between Weber's molecular-magnet conception, and the non-dimensional conception of permeability, however, is not generally recognized; consequently, there are many scientists to-day who advocate the Weber's theory of magnetism either in its original form, or in its modern modified form based either on molecular currents, or on electronic orbits, and they also advocate the dimensional conception of permeability.

In 1886, Ewing formulated his theory of permeability and magnetization based on Weber's conception. He thus explained successfully, the general forms of magnetization and hysteresis curves, and also other associated phenomena such as magnetic creeping. He also explained some of the peculiarities of hysteresis loops such as the failure of the loops to close, and of successive loops to retrace the preceding loops during the initial cycles.

Ewing's work was mostly qualitative: quantitatively, he had succeeded in making, what we might call the first approximation; that is, in computing the magnetic forces on the molecular magnets, he had taken into account only the nearest poles, and had left out of consideration the relatively distant poles of even the same molecules (Ewing: "Magnetic Induction in Iron," p. 172). In 1892, Steinmetz carried Ewing's theory of hysteresis one step further; Ewing had taken into account only one pair of poles, namely, the two nearest poles of a pair of molecules; Steinmetz took into account all the four pairs of the poles of these molecules (A.I.E.E. Trans., 1892, p. 718). His next effort was to be a more elaborate computation of forces on a molecular magnet due to a large number of molecular magnets in its neighborhood. It seems that this work was not completed, and in the meantime an unforseen difficulty had arisen.

In 1889, Rucker formulated his theory of "suppressed dimensions;" according to that theory permeability is a dimensional quantity; the dimensions are not yet known, but are believed to be related to the dimensions of velocity. This theory rapidly gained in popularity and is now accepted by a majority of scientists. As stated above, Rucker's theory and Weber's theory are opposed to each other, and that the acceptance of the one necessarily involves a rejection of the other theory. The contradictory nature of the two theories generally is not recognized, because those who accept both are generally content with a formal acceptance, without any attempt to carry each theory to its logical consequence.

In accepting the dimensional conception of permeability, we have perhaps unconsciously rejected a very valuable analytical instrument for magnetic research. In other words, our lack of correct and clear understanding of magnetic hysteresis, is the price we are now paying for the dimensional conception of permeability. This is not an argument against Rucker's theory. If the theory be true, we have got to accept it no matter what price we have to pay for it; but before we pay that or any other price, we must have some evidence in support of that theory.

Therefore, while our engineers are collecting data on magnetization and hysteresis, evolving ingenious methods for the work, it is for the physicists to tackle the fundamental problems in order to account for the phenomena in a rational way. The problem that seems to be at the root of most of the other problems in magnetics is, whether permeability is a dimensional or a non-dimensional quantity. Until that question is answered with convincing evidence in support of the answer, there seems to be no likelihood of a rational explanation of the magnetic phenomena.

**C. MacMillan:** The data given in the paper should prove valuable to designers of various types of electrical apparatus. The cases to which the results immediately are applicable are confined to those in which the superposed fields are in line with a common axis. However, the data should also afford assistance in cases involving more complex conditions, and field axes which are not necessarily in alignment. Such conditions occur, for example, in the magnetic circuits of induction motors. In the vicinity of the air gap, the general direction of the useful flux is radial, that of the leakage flux peripheral, yet in their use of common permeance paths, these fluxes approximate more closely to the conditions covered by the paper.

As shown in the paper, the fundamental a-c current may be taken to represent the d-c displacement mmf upon which is superposed the high frequency pulsation of mmf induced by the non-uniform and non-sinusoidal distribution of teeth and windings. The magnitudes involved bring this case into the class in which reduction of iron loss with high density might be anticipated since the flux displacement does, in practice, frequently exceed the critical values given in the paper. Thus, we may expect locally the conditions for reduced losses which rarely are encountered on a more extended scale on account of the large mmf's and currents required to establish them.

In applying the data on superposed losses, or losses due to superposed mmf's to the calculation of induction motor core loss, we have found that the computed loss may be brought into closer agreement with test results. However, in some cases, the calculated values exceed the test values. The discrepancy may be due in part, at least, to reductions of the type described in the paper, and to which due weight had not been given in the methods used for calculation. Where the discrepancies are in the opposite direction, it is more difficult to assign causes since they may be due to defective care in manufacture.

Attention has been called, in previous discussion, to the unsatisfactory state of our knowledge of magnetic processes. Even the discussor who contrasted favorably present knowledge of metals with present knowledge and lack of knowledge of non-metals, such as dielectrics, would probably make an exception in the case of the magnetic properties of metals. If the increased training in analysis advocated by Professor Karapetoff is successful in developing graduates of greater analytic ability, possibly this stigma may be removed from the record of engineers, namely, that with the consistent records of magnetic behavior before our eyes so constantly for so many years, we have hitherto failed entirely to interpret these records.

**B. M. Smith:** The method of measurement and equipment shown in this paper has certain refinements not used by previous investigators. It should, therefore, give results which are more reliable than hitherto obtained. The data presented by the author show agreement in several instances with those obtained by the investigators referred to, and also furnish new data beyond the range previously reported.

The fact that hysteresis loss decreases with superposed direct current has in the past given engineers encouragement to believe that it would be possible to obtain lower core loss in power transformers by this means. The data given in this paper, however, show that, although the hysteresis loss is decreased, there is a proportionately greater increase in the exciting current, which would indicate that the application of direct current could not be used for decreasing transformer losses. The tests, however, do not cover superposed alternating current.

In the numerous articles written on superposition of direct current on alternating current, it has been recognized that the hysteresis loss decreases when the hysteresis loop is displaced from its symmetrical position, but in none of these articles has an explanation of this phenomenon been given. It has, however, been mentioned that it is due to a change in shape and area of the hysteresis loop, but the writer believes it would be interesting if the author would give his explanation as to how this is affected.

**R. F. Edgar:** As pointed out by Mr. Gokhale, a fundamental explanation of the variation of hysteresis loss with displacement of the hysteresis loop apparently is unknown as yet, and further discussion of the various theories involved is beyond the scope of the paper. However, there is an association of the change of shape of the loop with its change of area, as suggested by Mr. Smith, which is given below.

Inspection of the series of loops published by several of the authors previously mentioned shows that as a loop is displaced upwards from a symmetrical position, keeping a constant amplitude of flux pulsation, the lower end tends to expand, while the upper end tends to contract. For combinations of flux pulsation and displacement which carry the upper end of the loop to very high densities, the contraction of the upper end apparently overbalances the expansion of the lower end, and the area of the loop is reduced.

# Variable Speed Constant Voltage D-C Generators

BY FRED B. HORNBY*

Associate, A.I.E.E.

***Synopsis.***—*Generators for producing essentially constant voltage when operating from a variable speed source have been developed. Two types of variable speed constant potential generators are described that obtain regulation without the use of regulators having moving parts. One type makes use of a thyrite regulator to obtain the desired characteristics. The other type is inherently self-regulating and, therefore, requires no external regulation. These generators are sufficiently flexible to allow a wide variation in their design and operating characteristics.*

* * * * *

APPLICATIONS for variable speed constant voltage d-c generators and generating systems have been many and varied. Generators with vibrating or carbon pile voltage regulators which have been used for variable speed constant voltage applications have been found inadequate because they will not operate satisfactorily when subjected to repeated vibration. The injurious effects of vibration have lead to the desire to have a generating system that can be regulated either by inherent generator characteristics or by a regulator that has no moving parts. The thyrite controlled generator system and the self-regulating generator have been developed to meet these requirements.

## THYRITE CONTROLLED GENERATOR

Before taking up a thyrite controlled generating system, it will be well to deal briefly with the characteristics of the material known as thyrite. Thyrite is a ceramic material having a mechanical strength about the same as high-grade porcelain. The most satisfactory shape for generator control is a disk 3 in. in diameter and 1/8 in. thick. The electrical characteristics of thyrite are a part of the ceramic bond and are not dependent on any fillers or mechanical contacts. The fundamental law of thyrite is stated by the equation $RI^2 = C$, in which $R$ is the resistance of the thyrite, $I$ is the current, $C$ is a constant coefficient, and $a$ is a constant equation. The exponent $a$ depends entirely upon the quality of the material and is less than unity, typically 0.72. The coefficient $C$ depends on the specific physical dimensions of the thyrite unit. The operation of thyrite is not dependent upon the temperature, but the material does have a negative temperature coefficient. This negative coefficient has about the same numerical value as the positive coefficient of copper. An increase in voltage across a thyrite unit will result in an increase in current by approximately the 3.57 power of the voltage increase. It is this negative resistance characteristic that makes it so useful as a regulator.

The connection of the thyrite unit as a control for a generator is shown schematically in Fig. 1, wherein the unit is in series with an auxiliary field which is wound on the same pole as the shunt field. The auxiliary field is so connected that the magnetomotive force produced by the auxiliary field is in opposition to that produced by the shunt field. If the generator terminal voltage increases, the thyrite allows proportionately more current to pass through the auxiliary field than passes through the shunt field, with the result that the difference in magnetomotive force of the two fields decreases, thereby decreasing the flux in the machine and limiting the increase in generator voltage. The performance of a typical thyrite controlled generator is shown in Fig. 2. As may be seen, the flux in the machine decreases as the speed of the generator increases, the flux approaching zero as a limit.

The thyrite acts not only as a regulator, but also as a stabilizer and makes it possible to operate the generator at fields much weaker than normally would be practical. Generators controlled in this manner have shown perfect stability, although the flux in the generator was less than 10 per cent of the normal flux. This type of control also will produce very good generator load regulation as shown in Fig. 3. Both the operating stability and the flat compounding are obtained by the regulator attempting to hold constant generator voltage. The effect of heating on the thyrite system is much the same as the effect of heating on a standard d-c generator. An increase in temperature will produce the usual drooping voltage characteristic.

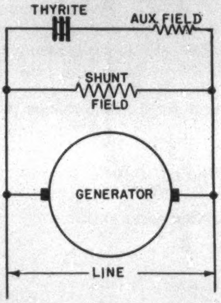

FIG. 1—SCHEMATIC DIAGRAM OF A THYRITE CONTROLLED GENERATOR

The design of thyrite controlled generators should be such that the peak of the flux curve is reached at approximately the rated base speed of the generator. Consider the design of a machine having ideal conditions wherein a straight line saturation curve is obtained. Saturation will further increase the necessary size of the machine. Since the heating of the fields is the limiting feature in the design of a thyrite controlled generator, a consideration of the fields necessary to produce the required characteristics will give an idea of the size of machine necessary.

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*General Electric Company, Lynn, Mass.

*Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10-12, 1933.*

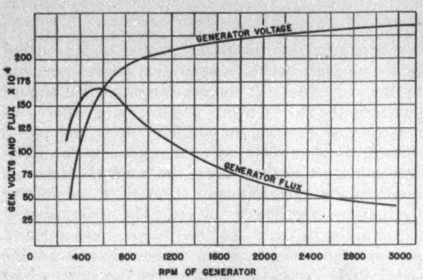

FIG. 2—SPEED REGULATION AND FLUX CURVES FOR A THYRITE CONTROLLED GENERATOR

### GENERAL CONSIDERATION OF FIELDS

Assume circuit connections as shown in Fig. 1.

Let

$A$ = shunt field ampere-turns
$B$ = auxiliary field ampere-turns
$AT$ = effective ampere-turns = $A - B$
$K_e$ = ratio of thyrite current for a given change in terminal voltage
$K_\theta$ = ratio of flux change, $\theta_2 = K_\theta \theta_1$
$K_v$ = ratio of voltage change, $V_2 = K_v V_1$
$K_s$ = ratio of speed change, $S_2 = K_s S_1$

Assume straight line saturation curve so that

$$V \alpha A - B$$

Since

$$\theta = \frac{CV}{S}$$

then

$$K_\theta = \frac{K_v}{K_s}$$

With this scheme of connection

$$A_2 = K_v A_1 \text{ and } B_2 = K_e B_1$$

$$A_2 - B_2 = K_\theta (A_1 - B_1)$$

$$B_1 = A_1 \frac{K_v - K_\theta}{K_e - K_\theta} = A_1 X$$

where

$$X = \frac{K_v - K_\theta}{K_e - K_\theta}$$

$$A_1 = \frac{AT}{1 - X}$$

Expression for total field ampere-turns at base speed

$$A + B = A_1 (1 + X) = \frac{AT (1 + X)}{1 - X}$$

*Example.* Consider a machine having 2 to 1 speed ratio and 1.5 to 1 voltage ratio.

$$K_s = 2 \qquad AT = 1{,}000$$

$$K_v = 1.5 \qquad K_\theta = \frac{1.5}{2} = 0.75$$

$$K_e = 4.5$$

$$X = \frac{1.5 - 0.75}{4.5 - 0.75} = 0.20$$

$$A_1 = \frac{1{,}000}{1 - 0.20} = 1{,}250 \qquad B_1 = 250 \text{ amp-turns}$$

$$A_1 - B_1 = 1{,}000$$

$$\text{Total ampere-turns in field at } S_1 = \frac{1{,}000 \times 1.2}{0.8}$$

$$= 1{,}500 \text{ amp-turns}$$

Ratio of total to effective ampere turns of $S_1 = 1.5$.

Examination of general equations and specific examples brings out two main facts:

1. The closer the regulation over a given speed range, the larger the field.

2. The greater the speed range, the larger the field for a given regulation.

The necessity of having the actual field winding over 1½ times the normal field requires a theoretical increase in the size of the machine. Saturation of the iron makes it necessary to have a still larger machine since with saturation the change in field strength is not reflected in change in flux. The necessary increase in field space together with the necessity of having low iron density results in a practical increase in machine size very close to the increase in field size given by the foregoing approximate calculations. Results have shown that the figure arrived at by such a calculation

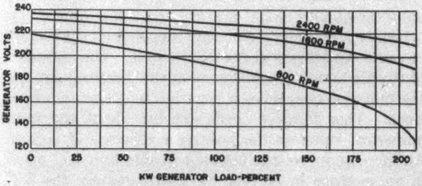

FIG. 3—LOAD REGULATION CURVES FOR A THYRITE CONTROLLED GENERATOR

can be used as an index to determine the necessary dimensions of a specific generator.

Obviously, the increase in frame size becomes an economical limitation as the output of the generator increases. This increase in cost and size may be readily overcome by applying an exciter to the generator and the thyrite control to the exciter field instead of the generator field. The exciter will be oversize, but since it is a small machine, this increase is a reasonable factor when it is considered along with the main generator. When applying an exciter, it is advisable to excite both of the exciter fields from the main generator terminals. This makes the action of the exciter directly dependent on the generator voltage.

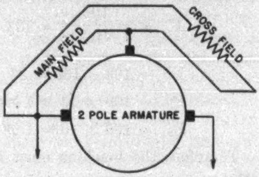

FIG. 4—SCHEMATIC DIAGRAM OF A SELF-REGULATING GENERATOR

The generator-exciter combination makes a thyrite system that is simple, economical, and capable of satisfactory operation in a wide variety of applications. There are, of course, limitations to this system and type of control, but these limitations have not been broadly determined; and since they are readily found when specific machines are considered, no attempt will be made to describe them.

### SELF-REGULATING GENERATOR

In his paper, *A D-C Generator for Constant Potential at Variable Speed* (A.I.E.E. TRANS., 1918, V. 37, Part II, pp. 1405-12) S. R. Bergman described a very practical machine for producing constant voltage, the regulation being entirely inherent. A machine giving regulation without a regulator of any kind has several advantages. The fundamental theory of this machine is described fully in Mr. Bergman's paper. Demands for this type of equipment have increased greatly, and speed ranges and duty cycles have become more severe. For this reason, it seems desirable to discuss further this machine and its design.

A schematic diagram of connections is shown in Fig. 4. Other connections are possible, however, and it would be well to consider some of these as they have a definite bearing on the design of the machine. The main field may be excited from a separate source, but it may not be excited from the main line of the generator without special connections and an auxiliary field as shown in Fig. 5. If the main field be excited from the main brushes of the generator without these precautions, the generator will experience difficulty in "building up," because the residuals of the main and cross fields are bucking each other. Also, the machine will have a tendency to reverse polarity if rapid changes in speed occur. Under all conditions, the cross field must be excited from the voltage produced by the main field flux. With connections as shown in Fig. 5, the main field may be connected across the main line and satisfactory operation obtained. The auxiliary field is connected in the same direction and is wound on the same pole as the main field; it acts merely as a "teaser" winding which starts the generator to build up and prevents a reversal of the generator polarity during the transient period.

When the generator is connected as shown in Fig. 4, the main field heating increases as the square of the increase in excitation voltage; thus it is necessary to design the field so that it will produce normal ampere-turns at the base speed and at the same time dissipate many times more than normal heating at top speed. The cross field produces normal ampere-turns at top speed and is, therefore, a normally balanced field. With the generator connected as shown in Fig. 5, the auxiliary field must be designed for normal excitation and many times normal heating; but the auxiliary field is in itself a very small field so that this problem is not serious.

From the preceding discussion it may be seen that connections shown in Fig. 4 can be used for generators having a small speed range, but for generators having a large speed range, the connections shown in Fig. 5 are better. If a separate source of power is available for exciting the main field, connections in accordance with Fig. 4 (except the main field excited from this separate source) are satisfactory for generators of any speed range.

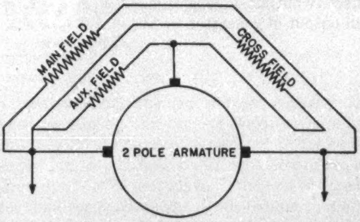

FIG. 5—SCHEMATIC DIAGRAM OF A SELF-REGULATING GENERATOR WITH AUXILIARY FIELD

Since the generator operates on the difference of two voltages, the size of this machine will be larger than that of a standard generator of the same rating. In these machines, heating of the fields is a limiting factor, but not the only one, for armature heating also affects the rating. The following consideration of the various factors gives a definite figure for the increase in size necessary for a given rating.

## DETERMINATION OF VOLTAGES INDUCED FROM MAIN AND CROSS FIELDS

Let

$X$ = volts induced from main field
$Y$ = volts induced from cross field
$Z$ = terminal volts
$S$ = speed ratio
$R$ = voltage ratio
$K$ = main field flux increase factor
$C$ = cross field flux factor
$I_r$ = rated generator current at base speed, including field current

$$X_1 - Y_1 = Z_1$$

$$X_2 - Y_2 = RZ_1$$

$$X_2 = KSX_1$$

$$Y_2 = CS^2Y_1$$

$$R(X_1 - Y_1) = X_2 - Y_2$$

$$X_1 - Y_1 = \frac{KSX_1 - CS^2Y_1}{R}$$

$$X_1(KS - R) = Y_1(CS^2 - R)$$

$$Y_1 = X_1 \frac{(KS - R)}{(CS^2 - R)} = X_1 m$$

where

$$m = \frac{KS - R}{CS^2 - R}$$

$$Z_1 = X_1(1 - m)$$

$$X_1 = \frac{Z_1}{1 - m}$$

Effective output of generator = $(X_1 - Y_1)\, I_r = P_e$; actual output of generator = $(X_1 + Y_1)\, I_r = P_a$.

## EXAMPLE

Consider a machine having a 2 to 1 speed ratio and 1.5 to 1 voltage ratio with connections as shown in Fig. 4.

$Z$ = 100 volts $\qquad K = 1.12$
$S = 3 \qquad C = 1$
$R = 1.5 \qquad I_r = 10$

$$m = \frac{(1.12 \times 3) - 1.5}{9 - 1.5} = 0.248$$

$$X = \frac{100}{1 - 0.248} = 133$$

$$Y = 133 - 100 = 33$$

$$P_e = 100 \times 10 = 1 \text{ kw}$$

$$P_a = 166 \times 10 = 1.66 \text{ kw}$$

Therefore the machine must be 1.66 times normal size.

Generators making use of the bucking field principle have been built for many years and their operation has been quite satisfactory. There are, of course, limitations to this type of equipment, but except the increased size, weight, and cost, the limitations are peculiar to the application and cannot be considered as general difficulties to be overcome. Detailed comparison of these two types of machines with each other and with other types of variable speed constant voltage equipment is outside of the scope of this paper. Such comparison when made should be on the basis of the total equipment including all regulating devices and controls, and not on the basis of the generator alone.

# Design of Resistance Welder Transformers

BY H. E. STODDARD*

Associate, A.I.E.E.

***Synopsis.****—Due to increased production demands, the speed at which resitance welders operate has been stepped up as much as four to five times during the last few years. This has been made possible in a large degree, by the development of new switching mechanisms that will allow a current dwell of a fraction of a cycle on a 60-cycle circuit.*

*This increased speed of welding has made it necessary to study very carefully the design of the transformer and the shape and spacing of the secondary circuits, especially the cooling and protection of these parts.*

*It has been necessary also to pay more attention to multi-transformer welders, where several transformers are used either for the purpose of distributing the secondary current to better advantage, or for the purpose of balancing the welder load on multi-phase circuits.*

IN the last few years manufacturers have been called upon to produce welders that will weld at very high speeds. Spot welder speeds have increased from a maximum of about 150 to 200 spots per minute of ten years ago to a maximum of 900 spots per minute today, with the indication that this speed can be increased to perhaps as much as 1,800 spots per minute. Also in the last few years control units employing grid-controlled gas or mercury-vapor filled electronic tubes have been developed and applied to spot and seam welders for high speed welding. The time of current dwell can easily be reduced to one cycle on a 60-cycle circuit. Also several switching mechanisms driven by synchronous motors have been developed and put in use and it is claimed that they will operate at such speed that the current dwell can be reduced to ½ cycle or less on a 60-cycle circuit.

Welders other than spot welders have been increased in speed, but not in the same proportion. Ordinary flash butt welding is being done at an average speed of about 7 sec for the complete welding cycle on work up to about 10 sq in. Smaller sections are welded in less time, and larger sections in longer time. Therefore the welders, including the transformers, are continually increasing in size and capacity for the same size of weld, and the problems of the design are being increased in proportion.

Very little technical work is involved in the ordinary design, but considerable experience is necessary in selecting the proper secondary voltage, estimating the correct power required, proportioning the transformer core and coils properly so that mechanical design of the welder is not upset, designing the secondary circuit from the transformer to the work, providing the proper shielding for the transformer, etc.

A resistance welding transformer has a peculiar duty to perform. It must be of great enough capacity to deliver the number of amperes at the weld required for welding the largest section for which the machine is used. It must also be of great enough capacity to permit of welding the greatest number of square inches per hour for which the machine is purchased. It must do all this without heating to a point to injure the insulation. Furthermore, it is not the internal resistance of the transformer only which tends to heat it, for there is the heat conducted back into the transformer secondary by conduction, and to other parts of the transformer by radiation and convection.

The problem is not to design a transformer of specified capacity, but to design a transformer and secondary circuit that will cause enough electric current to flow through the work and heat it properly so that with the correct application of pressure a weld is completed.

The transformer capacities are estimated mainly by considering the size of material to be welded, the speed at which it must be welded, the type of weld to be used, and mechanical design of welder. The types of welds are as follows:

1. Spot welds
    Projection welds (single projection, multi-projection)
    Point welds (single spots, spot seams)
2. Butt welds
    Upset welds
    Flash welds (manually controlled, mechanical controlled)
    Contact flash or high speed upset welds
    Butt seam
3. Line or seam welders
    Continuous
    Interrupted

In butt welding, the transformer capacity is influenced greatly by the type of weld, as flash welds require only 20 per cent to 25 per cent of the capacity necessary for contact flash welds, and slow upset welds require only about 25 per cent to 50 per cent of the capacity required for flash welds. If we assume that a flash weld will be made in 7 sec, then a slow upset weld will take about 15 to 30 sec, and a contact flash weld about 1 to 2 sec, provided the pieces to be welded are adaptable to either type of weld.

Multi-projection welding requires sometimes as much as two to three times the capacity for one weld times the number of welds. This increased capacity is principally due to the fact that nearly always one weld is partly made, first, causing an increase of current at that point. Therefore there must be enough capacity to take care of this. This increased capacity is also influenced by the shape of the work, size of weld, and the shape and size of electrodes when they may restrict the proper distribution of the welding current.

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*Thomson-Gibb Electric Welding Co., Lynn, Mass.

*Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N.Y., May 10-12, 1933.*

## TRANSFORMER CORE

The core is usually built up of 29 gauge silicon steel in one or two window shapes. Sometimes the single window cores are split and after assembly they are machined so that they fit together with little air gap. This split core is used when it is necessary or convenient to have an easy way of disassembling the transformer for changes or repairs.

## TRANSFORMER SECONDARY

The secondary may be either flexible for its entire length, or it may be solid and have a short flexible lead connected to the moving terminal of the welder. The flexible secondary is made up of thin copper strips, usually 0.005 in. to 0.008 in. thick and they may be made up of narrow strips and sandwiched between pancake primary coils (see Fig. 2), or of wider sheets and wound around the outside of the primary coils (see Fig. 1). There is some objection to both of these types of secondary. One objection to the narrow type is that the primary coils cannot be wedged properly, and the objection to the wide type is that the design of the transformer is not as adaptable to changes as the narrow type would be.

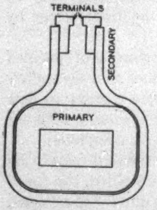

FIG. 1 (LEFT)—WIDE FLEXIBLE SECONDARY OUTSIDE OF PRIMARY COILS

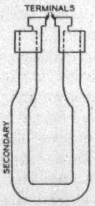

FIG. 2 (MIDDLE)—NARROW FLEXIBLE SECONDARY SANDWICHED BETWEEN PRIMARY COILS

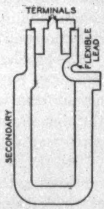

FIG. 3 (RIGHT)—CAST SECONDARY CONNECTED TO MOVING TERMINAL BY SHORT FLEXIBLE LEAD. SECONDARY SANDWICHED BETWEEN PRIMARY COILS

Solid secondaries are made of cast copper, cast aluminum, rolled copper, and sometimes of the work itself. Where castings are used for secondaries, they are usually water cooled by either casting steel tubing in cast copper, copper tubing in the cast aluminum, or by holes drilled for a water circuit. Cast copper is used principally and has less disadvantages than any other cast material. The disadvantages to cast aluminum are that it must be double the area of cast copper, and high resistance oxides form rapidly on the machined contact surface under the influence of heat and water. Rolled copper is used very little for solid secondaries, due principally to the difficulty of connecting the ends to the terminals of the welder, as each section of the secondary must be silver soldered or welded to a suitable header; since there is a large mass of metal, it is a difficult and expensive job. Rolled copper does make a good secondary, and on some welders where forced air can be used for cooling the transformer, it is used. See Figs. 3, 4, and 5 for different shapes of cast secondaries for butt welders, and Figs. 6 and 7 for shapes of circuits for small spot welders.

The secondary proper is shaped so as to minimize the eddy current losses. The terminals and flexible leads are designed with proper contact surface areas where electrical connections are made. These areas are of such size as to keep the current density to about 225 amp per sq in. when connected to aluminum; to about 550 amp per sq in. when connected to cast copper; other materials generally fall within these limits. Conditions often alter these values.

## PRIMARY COILS

The secondary voltage of a resistance welder is changed either by changing the primary voltage or by using a selector switch connected to tapped primary coils to change the turn ratio. Generally the minimum secondary voltage is 40 per cent to 50 per cent of the maximum. This, of course, depends upon the kind of welding to be done. Usually about 10 to 16 different secondary voltages are provided; therefore 6 to 8 taps are necessary for the secondary voltage range. The tapped primary is generally used, although there is some objection to it. When the transformer is being operated on the maximum secondary voltage, the voltage across the outside turn of the primary coil is about two times the primary voltage. Also as about one-half of the primary is out of the circuit, the magnetic leakages may be increased considerably, but by using care in the design these objections can be minimized to a large extent.

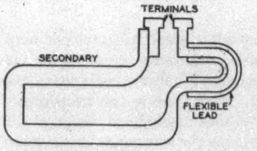

FIG. 4—CAST SECONDARY CONNECTED TO MOVING TERMINAL BY FLEXIBLE LEADS. SECONDARY SANDWICHED BETWEEN PRIMARY COILS. TRANSFORMER OFFSET FROM WELD LINE

Sometimes especially in large welders the coils are not tapped, but an autotransformer with tapped coils is used for secondary voltage variation, in this way getting around the objections mentioned; but in doing so there is added another piece of apparatus which must be installed near the welder and therefore is in itself not desirable. Generally either type of transformer is equally acceptable. However, on some of the larger types of welders, autotransformers are demanded and in addition sometimes an inductive voltage regulator is used to get micrometer voltage adjustments between taps on the autotransformer.

The primary coils and the coils of autotransformers are usually wound of bare copper strip and insulated between layers with asbestos paper tape. As little insulation as practical is used on the outside of the coil in order that the heat may be dissipated as rapidly as possible. Although the secondaries of most welder transformers are water cooled, this helps very little in cooling the primary, and the natural air draft is depended upon for this cooling.

### TRANSFORMER RATING

The Resistance Welder Manufacturers Association rating is based on 50 per cent duty cycle, which was selected because very few welders are operated at higher than 50 per cent duty cycle and because it corresponds quite closely to the majority of welders in use previous to this rating. The primary is designed for a current density of 1,800 amp per sq in.; the secondary for 1,600 amp per sq in. if made of cast copper; 800 amp per sq in. if made of cast aluminum, and the core is designed for a density of 70,000 lines per sq in. at the maximum secondary voltage.

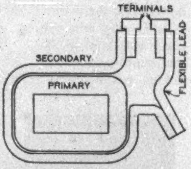

FIG. 5—WIDE CAST SECONDARY TO FIT OUTSIDE PRIMARY COILS. TRANSFORMER OFFSET FROM WELD LINE

### MECHANICAL PROBLEMS

The mechanical problems in the design consist of: First, shaping the transformer so that it fits into the welder properly; second, making the core and core clamping frames, primary coils, and secondaries of such shape and material that they can be made and assembled without too great an expense, and without sacrificing more than is necessary in the efficiency and power factor of the completed welder; and third, the shielding of the transformer from the metal thrown off by the weld and also from water and oil.

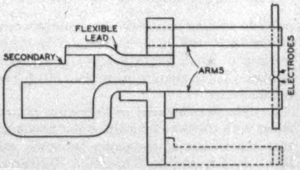

FIG. 6—TOP CONNECTED SPOT WELDER

The fact that a large percentage of designs are for special apparatus where perhaps only one transformer is to be built, makes these problems quite important. Shaping the transformer properly so as to fit the welder is relatively simple, and can usually be accomplished. A 40-kva or 50-kva transformer can be built so it will go in a space only 4 in. wide; of course it must be extended considerably in other directions. The core and clamping frames also are easily handled. The difficulty comes in the secondary, secondary leads, and the terminals. The secondaries should be made as high and as thin as possible. Where water cooled secondaries are called for, they must be thick enough so that a tube can be cast in for a water duct, and this requires that the casting be about 0.5 in. thicker than the diameter of the tubing to prevent its floating out. Also, as far as possible, the tubing must be cast in so that it is parallel to the current flow, and the tubing must be as straight as practicable so that it can be cleaned out if it fills up with rust or dirt. The finished secondary is always a compromise between good electrical practise and the desired mechanical features.

The terminals of the welder are necessarily well cooled, not only to dissipate the heat due to the flow of current, but to dissipate the heat conducted into them by the weld itself, and since the terminals are under very heavy pressure, it is necessary to keep the temperature as low as possible.

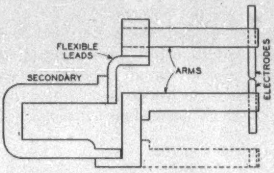

FIG. 7—BOTTOM CONNECTED SPOT WELDER

The flexible leads are also a compromise. Electrically they should be as short as possible, and mechanically they must be long enough to allow the terminal plenty of movement, and also they must be of proper shape to insure long life.

The mechanical difficulty met with concerning the primary coils, is to bring out the taps and the start and finish of the coils so that the minimum space is required, also to brace the primary effectually against the surges that are always present.

The shielding of the transformer also is very important, especially on flash butt welders. It is necessary to keep the metal thrown off by the weld from the primary coils. This metal is in the form of fine dust and if allowed to sift in between coils soon penetrates the insulation and causes short circuits or grounds. Also, there is always a large amount of water used around resistance welders, especially line or seam welders, where the work is sometimes flooded with water. Therefore, it is necessary to make the primary coils nearly waterproof.

### MULTIPLE TRANSFORMERS

In some welders it is necessary to use more than one transformer. Four general types of multi-transformer welders are:

1. Welders for making fabric for reinforcing mats used in concrete road building, where as many as 32 transformers are used and 32 welds are made simultaneously, each transformer making a weld which is separated from the next weld enough so that no particular difficulty is experienced.
2. Large spot welders are sometimes provided with two transformers, one transformer on the bottom and one on the top of the work. Each end of the secondary of both transformers is connected to an electrode, the top electrodes being directly over the lower electrodes when the work is placed between them. The secondaries are in series. No particular advantage is gained however.
3. Welders used for making very long butt welds where multi-transformers are convenient for distributing the current properly over the entire weld. These transformers are connected in parallel on a single phase circuit.
4. Large projection spot welders where the work is distributed properly. Three transformers are sometimes used and connected each to one leg of a three-phase circuit.

In the third type of welder mentioned where the transformers are operated in parallel, the principal difficulty is in the secondary circuits. Unless these circuits are all of the same resistance and impedance, the current distribution will not be correct.

In the fourth type mentioned, the same difficulties are experienced and in addition to these the fact that the work causes a partial short circuit between phases makes it difficult to design electrodes to minimize this short circuit so that the work can be done efficiently.

### POWER FACTOR

The power factor of resistance welders varies considerably with the type and construction of the apparatus. On some types of welders, it may be as high as 65 per cent or 70 per cent; on other welders, it may be as low as 20 per cent.

Resistance welder manufacturers are of course interested in methods of increasing this power factor. The first idea is to better the design of the transformer and connections, but since the design is limited so closely by mechanical requirements for protection of the transformer and for the proper movement of the welder terminal, very little increase in power factor may be secured. Therefore, it seems as if any substantial increase of power factor must be made by the use of some outside piece of apparatus.

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## Discussion

**Warren C. Hutchins:** As indicated by the author, developments in resistance welding have been very rapid in the last few years. In fact in the writer's company one man was given the task of correlating data on resistance welding with reference to the power, time application, pressure of electrodes, recommended speed of travel for various types of spot and line welding. After this particular individual had spent approximately 3 or 4 months on this work and had collected enough information to fill several volumes, an electronic tube control named thyratron control was furnished to the Works Laboratory for experimental purposes. After about two or three weeks experimenting, it was found this control permitted welding in such greatly reduced time periods for spot welding and at such greatly increased linear speeds for line welding machines that practically all of the data previously collected were worthless.

Thyratron tubes were first applied to controlling resistance welding machines only a few years ago. The development of this control passed through the following stages:

1. To replace the mechanical contactors and eliminate the maintenance cost of the contactors. The average expected life of thyratron tubes for this service is 10,000 hours. This control was used for welders up to 350 kva capacity. For timing the on and off period a small 1-ampere switch was used. This switch usually was cam operated and the accuracy of timing was no better than the switch.

2. To the first control developed, a thyratron synchronous timer was applied which eliminated variations in the time current supplied to the welding machine. This permitted more consistent welding and increased welding speed. It also made possible welding in exactly one cycle or any multiple of one cycle of any frequency up to approximately 500 cycles. It permitted welding of some alloys not previously satisfactorily resistance welded. There are now more than 60 of these controls operating satisfactorily.

FIG. 1—ONE-HALF CYCLE THYRATRON CONTROL PANEL

3. (The development of thyratron control has been so rapid along with the development of the resistance welding apparatus that the author of the paper probably was not aware of this third development.) Thyratron control is now available for welding in very short periods. For instance ½ cycle, ¼ cycle or less.

The half cycle thyratron control has proved its worth in both the tube manufacturing department of the General Electric Company and in the manufacturing department of the RCA Radiatron Company.

A midwestern manufacturer had a welding machine which apparently was too small for the jobs being done; the welder transformer overheated and the control was a non-synchronous contactor. Thyratron control was applied to this welding machine, with the results that the transformer no longer overheated. The temperature rise was measured and found to be only 15 deg C (with a mechanical contactor the transformer overheated which means that the temperature probably exceeded 60 deg C rise).

There are 3 main reasons why the heating of the welder transformer might be greater if a non-synchronous contactor is used than when thyratron control is used. They are:

1. Where a non-synchronous contactor is used variations in the time of power applications will result. It is necessary to adjust the heat setting of the welding machine so that a satisfactory weld is made when the time element is shortest. This means that when the contactor passes current for longer periods, excessive energy is handled in the welder transformer resulting in heating.

Where thyratron control is used, the welder transformer is adjusted to produce a satisfactory weld for one time setting. The thyratron control accurately times to the same number of electrical cycles for each weld, and therefore no excess heat is handled by the welder transformer.

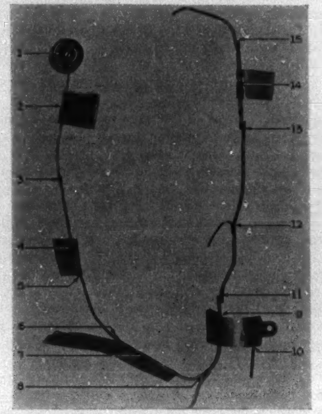

Fig. 2—Resistance Welds of Various Metals Made with Thyratron Controlled Welder

1—Copper wire and brass
2—Sheet nickel and soft nickel wire
3—Soft and hard nickel wires
4—Sheet nickel and hard nickel wire
5—Hard nickel and molybdenum wires
6—Molybdenum and invar wires
7—Perforated nichrome and invar wire
8—Hard nickel and invar wires
9—Invar wire and sheet monel
10—Sheet monel and molybdenum wire
11—Two invar wires
12—Soft nickel and invar wires
13—Invar and ascaloy wires
14—Ascaloy wire and nickel sheet
15—Ascaloy and hard nickel wires

2. Where a non-synchronously operated contactor is used, relatively long welding times are necessarily used (10 cycles or more), and a large percentage of heat is wasted by radiation and conduction of heat by the electrodes during the time the weld is being made. This results of course, in excess heat or energy being handled by the welder transformer.

Where thyratron control is used the time of power application usually is shortened a great deal, causing the weld to be completed in probably two or three cycles or less, and preventing excessive radiation and conduction of heat away from the weld.

3. With a mechanical contactor, it is entirely probable that the circuit is closed or opened at the zero point of the voltage wave. At the instant the contactor is closed, the flux in the transformer is at practically zero or only of residual value. In the first ¼ cycle, the welding transformer core reaches its full load excitation, and the balance of the first half cycle probably will result in over-saturation of the transformer, resulting in a tremendous current surge, which will be several times full load current (dependent upon the design of the particular transformer). After the transformer core becomes saturated it can no longer transmit the power to the secondary of the transformer. These surges can occur every time the circuit is closed and result in heating the transformer without delivering a proportional amount of power to the weld.

Where thyratron control is used, it is adjusted so that the circuit always is closed at the peak of the voltage wave, resulting in only normal saturation of the welding transformer before the alternating voltage reverses. The result is that stable operation is established from the start and no peak surge of current occurs.

As a result of these findings it has been predicted that resistance welding transformers can be rated higher than previously without increasing the amount of iron, provided thyratron control is used.

The author of the paper has stated in his concluding paragraphs that the resistance welder manufacturers are of course interested in methods of increasing this power factor—which is stated to be between 20 per cent and 70 per cent. It certainly is true that a load of only 20 to 70 per cent power factor is undesirable from a power generation standpoint. Worse than power factor however, is the fact that the load is single phase and intermittent and often causes light flicker. A number of power companies in this country among which are a power company in New Jersey and another in the State of Massachusetts, have insisted upon the manufacturer paying a penalty for this single-phase power, another penalty for the low power factor, and a third penalty for the intermittent operating characteristics. In another location it has been stated that a manufacturer is paying $3,000 premium per month for the privilege of using single-phase power from a public utilities line. This $3,000 is to cover the expense for extra single-phase line and necessary transformers to tie this load in to a high capacity network which runs within several miles of the particular manufacturing plant and to compensate for the unusual power demand.

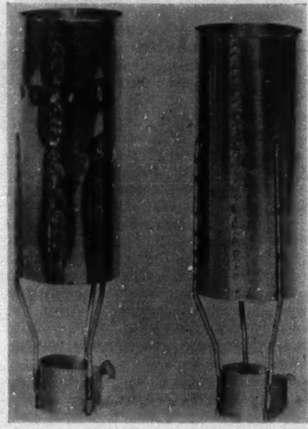

Fig. 3—Special Grid Assembly (Left) Welded On Manually Controlled Welder (Right) Welding in ½ Cycle

All of the above objectionable features or characteristics of the resistance welding load can be overcome by the application of motor-generator sets. More details on this application of motor-generator sets may be found in articles by the writer: "Problem of Power Supply for Resistance Welding," in the December 31, 1932 issue of *Electrical World* and "Balancing Welding Loads on Shop Lines," in the March 1933 issue of *Factory Management and Maintenance.*

**S. T. Maunder:** One point should be emphasized for the benefit of the industry at large. The requirements for secondary voltage and capacity usually are much higher than anticipated. For example, if it is thought that 3 volts are sufficient at the terminals of the weld, then very likely the terminal voltage of the transformer should be close to 10. The capacity is increased in the same proportion. This difference is caused by underestimation of requirements at the weld, larger current flow than was presupposed and too large drop in the terminals or lines to the weld. The drop mainly is due to excessive reactance in the lines, which often is nearly 100 per cent.

It has always been the practice to recommend that adequate tests be made before determining the capacity and voltage of welding transformer equipment.

## RADIO AIDS TO AIR NAVIGATION*

(Green and Becker)

**W. M. Thompson:** The system described in the paper appears adapted particularly for operation over fixed airways, although it appears practicable to use the system when flying toward or away from any suitable transmitting source. This method can be practiced roughly by using almost any aircraft radio direction finder and comparing the bearings with the magnetic compass to obtain the angle of drift when flying a known course but such application lacks the automatic feature of the present development. Actual flights made with only the inductor compass and associated control equipment have demonstrated to certain naval flyers that the automatic steering feature has many desirable attributes as it leaves the pilot with fewer controls to manipulate during flight.

The radio direction finder described as a part of this development appears to incorporate certain novel features but it is subject to certain errors which are inherent in such a system. For example, the output of the direction finder loop indicates a minimum when the plane of the loop is normal to the resulting wave front and such indication may not give the correct bearing unless corrections are applied to compensate for the disturbance caused by the structure of the plane. Propagation phenomena such as the well known "night effect" are encountered which may produce errors or make bearings difficult to obtain. Troubles of this sort can be minimized by using transmissions in that part of the radio frequency spectrum where experience has shown these effects to be a minimum but it is felt that such trouble should be pointed out in order to avoid conveying an impression that perfection has been obtained.

Then operational difficulties attend the use of such delicate devices for in effect a radio direction finder is a sort of bridge which must accurately be balanced if the results are to be accurate. This requires a design where the operating adjustments do not cause a shift in the bearing. The sensitivity must also be sufficient to avoid too much zig-zagging along the desired course.

Similar comments apply to certain forms of range beacons. This is illustrated by the fact that a certain pilot flying a course laid down by a beacon found himself being guided farther and farther to one side of his goal. Subsequent investigation disclosed that the gradual failure of a capacitor in the transmitting equipment caused this shift in bearing. Such an error was only apparent to the pilot by reason of clear weather and knowledge of the territory over which he was flying.

From a naval point of view it might be well to point out that a radio silence by the ships of the fleet probably will be mandatory when the fleet is at sea during wartime and that the only radio available will be that from the large shore stations. Due to the distance of the fleet from these shore radio stations, the possibility of interference is very great.

The above comments are not intended to derogate from the excellent development described to-day, but rather to emphasize the need for intelligent operation of all scientific equipment in light of its capabilities, for defects in such equipment may produce errors at possibly rare intervals which are difficult to detect.

**J. H. Dellinger:** As stated by the authors, the paper is principally on certain new types of equipment, but it gives also an interesting general survey of the whole field. In the fourth paragraph it is stated that radio methods for course and position determination fall under three headings, *viz.*, range-beacons, ground direction finding, and direction finding on the aircraft. For completeness there might be added to this list: directive beacons of other types than range-beacons (*e.g.*, rotating directive beacons), marker beacons, and altitude indicating methods. Of all these methods, there is perhaps the greatest field for development at the present time in direction finding, and it is fortunate that the authors have devoted particular attention to this point. The difficulties of thorough control of phase adjustments under all conditions of operation have retarded past development, and it is noted that this is receiving special attention in the new direction finder.

The following paragraphs summarize the development of a complete system of radio aids for the blind landing of airplanes. This work has been done in research extending over the past four years by the Bureau of Standards serving as the Research Division of the Aeronautics Branch, Department of Commerce. The system described meets all the requirements laid down by Messrs. Green and Becker in the second paragraph of the paper under the heading "Landing Aids." It has recently been demonstrated to the public in a series of completely blind landings under practical operating conditions.

This system gives position in all three dimensions—lateral, longitudinal, and vertical—which is the information that the pilot must have to make a landing. Lateral position is given by a runway localizing beacon, longitudinal position by marker beacons, and vertical position by a landing beam.

Work on this research project was divided into three stages, the first of which consisted of fundamental experiments and research to develop the basic component parts of the system, including the runway localizing beacon, marker beacons, landing beam, and suitable radio receiving and indicating apparatus for use in the air. The second stage consisted of the practical development of these component parts, fitting them together to form a complete system and finally demonstrating the practicability of the system through the medium of an extensive series of hooded landings, conducted by the Aeronautics Branch at its experimental flying field at College Park, Maryland. The third stage of the development, which involves the testing of the complete system experimentally under the conditions obtaining at a commercial airport, is under way at the Newark, N. J., Municipal Airport where the city of Newark has cooperated in the installation of the system.

The work at the Newark Airport includes fog landings as well as hooded landings. The former are, of course, more representative of operating conditions. While the Newark installation is not for service use in air passenger operations, it affords an opportunity for cooperative experimentation with air transport operators.

This system of landing aids is so designed as to require a minimum of special equipment on the airplane and to provide maximum convenience to the pilot. It is an airport system, all of the radio transmitting equipment being located on the ground at an airport. The lateral localizing of the runway is given by a small radio range-beacon of visual type operating on a frequency in the neighborhood of 300 kilocycles. The vertical direction is provided by a landing-beam transmitter operating on about 100,000 kilocycles; this gives a radio beam which is directive in the vertical plane, and marks out a line of equal received intensity in space which is tangent to the ground and suitably curved for the operation of landing. Longitudinal position is furnished by two marker beacons, low-power radio transmitters which give the pilot special signals, one of which he hears as he passes over a point 2,000 feet before the edge of the landing field is reached and the other is heard at the edge of the field.

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*See page 738.

The pilot hears the marker-beacon signals in his headphones. The indications from the runway localizing beacon and the landing beam are received on a single instrument with two pointers. One pointer is vertical and tells him his position laterally, and the other is horizontal and tells him his position in the vertical plane. By so operating the airplane controls as to keep the two pointers crossed at right angles, like the crosshairs of a gunsight, the pilot keeps the plane on the proper path for landing. When he hears the second marker-beacon signal he levels off and lands. The airplane equipment includes a distance indicator and other auxiliary aids.

Many auxiliary problems have been worked out, such as the coordinating of two-way telephone communication with the other radio devices, and the provision of a monitoring arrangement for the tests of the system. Experiments also have been made to adapt the equipment for use with all wind directions. The runway localizing beacon has been successfully operated in a pit below ground level, thus permitting its use in the center of a landing area. The experience at Newark, however, indicates that in practice it may not be necessary to provide service throughout 360 deg. In the Newark installation the runway localizing beacon and landing-beam transmitter are located northeast of the field, northeast being the direction of the prevailing winds during times of low visability. Both of these transmitters are capable of serving any direction throughout a 45 deg sector, which is sufficient to care for the wind conditions.

**P. V. H. Weems:** When not in sight of known landmarks, there are only two methods of fixing the position of aircraft in flight. We may apply the celestial navigation methods long used by the mariner, or else we may utilize the directional characteristics of radio waves. Celestial navigation is not available in fog, while on the other hand, it is a relatively simple and inexpensive method wholly self-contained, that is, it requires no cooperation of equipment or personnel outside the plane. Radio is independent of fog or other low visibility, but it does require assistance from equipment and personnel outside the plane. Furthermore, radio equipment is relatively expensive and complicated.

The most promising feature of radio navigation is the fact that so much has been accomplished in such a short time. Radio is a new art. In fact, most of us have grown up with it. With so much progress made in such a short time, it is logical to assume that another decade will result in the simplification and improvement of radio aids to air navigation to the point where it will be indispensable and almost universally used.

The science of air navigation is an extensive and difficult subject. The future will require navigation specialists who devote full time to the subject. In fact, during the development stage, full time may be devoted to radio alone to good advantage. Regardless of the preferred method, one fact must be kept in mind, *we should use all means available for the safe navigation of aircraft.* This includes dead reckoning, radio, and celestial navigation. The remainder of this discussion is restricted to radio; those interested in the other two methods are referred to "Air Navigation," (McGraw-Hill) for details.

Aside from its value for rapid communication in flight, radio navigation equipment is becoming standard equipment for planes in scheduled passenger flight. The widest use for radio for navigation purposes is found in the simple course indicators for use with the airway beacons on established airways. There are various types; aural, visual, or a combination. Also, the direction finder may be located either in the plane or on the ground. The details of these devices are explained in detail by the Department of Commerce "Air Commerce Bulletin," or by literature furnished by the manufacturers.

The ultimate goal of the air navigator is an automatic radio "super-metal mike" which will steer a plane continuously on its direct course regardless of wind drift. Such a device is the G-E automatic steering control with automatic radio drift correction. The writer was privileged to see two impressive demonstrations of this equipment. While the details of this equipment are in the development stage, the basic principles are definitely established. It should now merely be a question of time, intensity of demand, and the generous backing of the government, before a plane can take off and fly surely in a direct line to any desired point merely by grinding in the "address" of the destination. The address is given in the form of the course to be steered which is set for the automatic steering device. The plane will then take up a course at an angle to the true course equal to the wind drift and "crab" in a direct line to the destination. The latter part of the paper gives the details of this device and in Fig. 8 illustrates the demonstration equipment. In the writer's opinion it is difficult to over-estimate the value of this development to future aviation. With the simple addition of means for observing bearings received from a second station, the air navigator is enabled not only to proceed direct to his destination, but he may also determine his progress along the course at will.

The research necessary for the development of this and other equipment is expensive, and can only be carried out by the government or by large corporations such as the General Electric Company. The government should back the efforts of the General Electric and other firms by placing orders for the finished product, and by giving prizes for methods and equipment meeting the required rigid specifications.

**C. F. Green:** Three comments coming from Commander Thompson's discussion should be noted:

The metal structure of an airplane introduces errors in the compass bearings obtained with radio, which are comparable with those obtained on the magnetic compass. These can be compensated for in much the same way either by using a correction card or a correction cam in the controller circuit.

Errors obtained by a shift in apparent direction of wave propagation caused by interference of the reflected wave have to date been corrected only by special receiving and transmitting loops. It is believed that this method will be perfected so that accurate bearings may be obtained 24 hours of the day.

The value of radio compasses in war time will depend a great deal on the particular countries engaged. During the last war the high power low frequency stations, such as New Brunswick, N. J., Nauen, Germany, Bordeaux, France, and Carnarvon, Wales, worked almost continuously, and in Europe it would be rather difficult consistently to blanket out these stations. Any broad interfering wave transmitted to cause interference would have very little range.

Doctor Dellinger's timely short description of the system now undergoing tests at Newark, N. J., is of special interest since it is the result of extended work. The authors agree heartily with Commander Weems in his italicized words, not only in regard to navigation but also concerning other matters contributing to safety in flight.

# Radio Aids to Air Navigation

BY C. F. GREEN* and H. I. BECKER*
Associate A.I.E.E. Non-member

IT IS considered advisable to state in introducing this paper that its principal subject matter covers equipment which is believed to embody new and interesting features, but that refinement in detail and further testing are still necessary to reduce it for service. If so reduced its adoption will depend on its ability to compete with other systems of navigation from the standpoint of application, accuracy, simplicity, reliability, weight, size, and cost.

Radio has played an outstanding part in the promotion and maintenance of regular scheduled flight and safety in air transportation. In a relatively short time it has become an essential means of communication and navigation, and is steadily increasing the number and extent of its applications. It is particularly useful because it furnishes the navigator with reference axes and points.

One- and two-way communication have placed at the disposal of the pilot: weather information at points along the route, traffic conditions on the airway and at the terminals, assistance in case of trouble, and in isolated cases almost the sole means of effecting a landing in low fog at the terminal airport. Stations along the federal airways, installed and maintained by the Airways Division of the U.S. Department of Commerce, give weather information collected from 93 weather stations by teletype, while stations of the individual operators handle dispatching, traffic direction, and related matters.

In general, radio methods for course and position determination fall under three headings: (1) range beacons, (2) direction finding of aircraft position by ground stations, and (3) direction finding on the aircraft itself.

In the United States the first has been employed almost exclusively. The Department of Commerce has installed two types of radio range beacon stations along the federal airways of the country. The aural type making use of code signals indicates, by the interlocking of the "dash-dot" and "dot-dash" into one long dash, that the plane is on the course; periodic station-identifying code letters indicate the course followed. The visual type employing two modulation frequencies and a tuned reed indicator shows flight along the course by equal amplitude of reed vibration. Both systems have been described in much detail in various journals.[1,2,3,4,5] The aural range beacons have been in use since the establishment of the airways, while developmental visual stations have now led to the construction of a considerable number of this type. Continual progress is being made in these services, resulting in such improvements as simultaneous telephone and range beacons, T-L antenna system to overcome "night effect," and the reed converter for visual indication.

Directive beacons, with the straight airway between them, are supplemented by small marker beacons at intervals along the route. These low-power transmitters, giving a characteristic signal, serve to indicate position along the airway.

Here, then, is a system of communication, a system of navigation along fixed routes, and means of getting approximate position on the route, which have been of inestimable value.

Navigation along independent routes requires direction and position finding either (1) on the ground with transmission to the aircraft as in use on the airways of Europe or (2) on the aircraft by direction finder or compass. In the former, ground direction-finding stations triangulate on the characteristic radio signal of the plane and, having determined the craft's position by combining their individual readings, transmit it to the plane. This system has the disadvantages that the indications are not continuous and that the position indicated is that occupied by the plane some time previous.

Direction finders based on minimum signal employing loops aboard the craft are in extensive use on marine vessels, lighter-than-air craft, and also to some extent on airplanes. This equipment makes possible the fixing of position by triangulation, and guidance along a route toward or away from a transmitting station by maintaining the indication at the minimum; but it does not show that a deviation is to the right or left of the course. A radio compass makes possible direction finding and gives right and left indication of deviations from the course.

## RADIO COMPASS

An ideal radio compass for use in controlling the course of an aircraft would be one that would give right and left indications on both continuous and modulated wave radio signals sensitive around the zero position, and not destroy the characteristics of the signals used in communication.

Radio compasses have been in use for years along the coast to determine the position of ships. In these installations loop antennas are used to get the line between the ground station and the ship, but the loop alone does not tell at which end of the line the ship is located except, of course, that on the east coast the ship naturally will be to the east of the station. In order to determine from which end of the line the signal is coming it is necessary to compare the output of the loop antenna with the output of a vertical wire antenna. This is done by combining the two outputs and noting the effect in head phones when the loop is swung from one side of zero to the other.

A radio compass for use on aircraft must give right and left indications on a visual indicator so that if the pilot when flying toward a radio station turns the

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*General Electric Company, Schenectady, N. Y.

1. 2. 3. . . . See bibliography at the end of article.

*Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10–12, 1933.*

ship to the right, the indicator must turn to the right; if he is flying on a course away from the radio station and the ship is turned to the right, the indicator must show left, indicating that he is flying away from the radio station. Several radio compasses have been developed to give these indications. In general these contain some form of a synchronized switching device which rapidly switches the polarity of the loop with respect to the vertical antenna and at the same time switches the rectified audio frequency output using a zero-center indicating device; this gives a sense of direction if the loop increases the voltage picked up on the vertical antenna when connected for right indication, and bucks when the indicator is connected for left indication. This principle gives fairly satisfactory results, but it destroys the characteristic of the signal for use in communication and the accuracy is effected by phase-angle shifts in the radio receiver due to any regeneration that might be present.

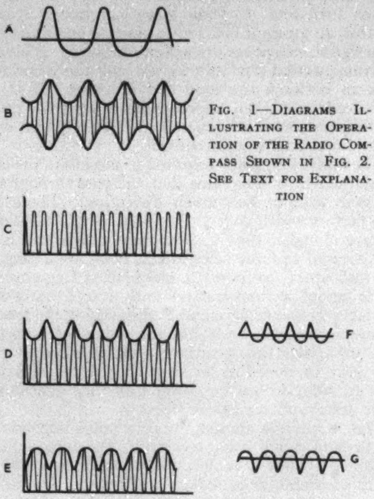

Fig. 1—Diagrams Illustrating the Operation of the Radio Compass Shown in Fig. 2. See Text for Explanation

A radio compass utilizing an entirely different principle has been under development; it does not depend on synchronizing the input and output of the radio receiver, and it does not destroy the modulation that might be present on the radio signal.

A loop antenna has directional characteristics in that the voltage induced in it becomes a minimum when the loop is normal to the direction of the radio wave, whereas a vertical wire antenna has no directional characteristic to waves approaching in a horizontal plane. Also the polarity of the loop with respect to the vertical wire antenna can be reversed by rotation; thus it is possible to use the voltage from the loop to buck or boost the voltage induced in a vertical wire.

The foregoing describes a method of indicating when the loop is not normal to the direction of propagation of the radio wave and also to which side it is turned. The next step is to transform the combined radio frequency energy from the loop and vertical wire to direct current which will reverse when the loop is turned from the bucking to the boosting position. This is accomplished by modulating the output of the loop with an audio frequency having a wave form as shown in Fig. 1*A*. This wave form is maintained through the radio receiver and audio output to a non-linear resistor in series with the visual indicator. A non-linear resistor is one in which the current does not change in proportion to the applied voltage; thus if an alternating current having a wave form as in Fig. 1*A* is applied to the resistor, the polarity of the wave having the highest peak value will cause more current to flow than the opposite polarity even though the rms values of both sides be the same. This increase in current from one side of the wave causes an indication in the d-c indicator and if the alternating current be reversed the indication will be reversed. Turning the radio loop from its zero position to one side or the other causes the peak side of the audio frequency output of the receiver to appear on one side of the wave or the other.

In Fig. 1*B* is shown the radio frequency envelope of output from the loop, which does not appear except when the loop is turned off normal; this is combined with the steady wave Fig. 1*C* from the vertical antenna. Figure 1*D* shows the resultant when the loop is turned in the proper direction to cause its voltage to add to that in the vertical antenna, and Fig. 1*E* shows the resultant when the two voltages are bucking. Figures 1*F* and 1*G* show the resultant a-c rectified currents from the radio receiver detector. When the aircraft is on its course, the radio loop is normal to the radio wave and the voltage across it is a minimum. Therefore there is no effect of the compass attachment transmitted to the receiver and

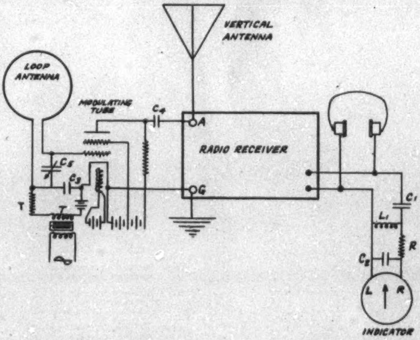

Fig. 2—Schematic Diagram of Radio Compass for Air Navigation

head phones, thus allowing the receiver to be used for communication purposes.

Referring to the schematic diagram, Fig. 2, the compass effect is transmitted through condenser $C_4$ to the antenna binding post of the receiver, and the audio frequency output is connected directly to the head phones and indicating system. Condenser $C_1$ and inductor $L_1$ are used to prevent excessive voice modulation from appearing on the indicator; $R$ is the non-linear resistor and $C_2$ is a smoothing condenser. The wave shape Fig. 1 is obtained by the action of resistor $R$, and the grid current in the modulating tube; this wave shape can be duplicated by combining the fundamental and second harmonic in the proper amplitude ratio and phase angle difference. Thus it is possible to modulate the loop energy with an audio frequency $f$ and combine it with a $2f$ frequency at the non-linear resistor; but any shift in phase relation caused by a delayed action in the radio receiver would tend to make the indication insensitive, or if carried too far the indicator would show reversed directions. This difficulty is a common experience with the type of compass that depends on the synchronized switching between the radio receiver input and output circuits, and prevents the use of any form of regeneration. With the compass just described, regeneration up to the point of oscillation does not interfere with the accuracy of the compass attachment—in fact when the receiver is oscillating as used for continuous wave telegraph reception compass bearings can be obtained, but the sensitivity of the overall system is considerably reduced because of the overload on the detector stage.

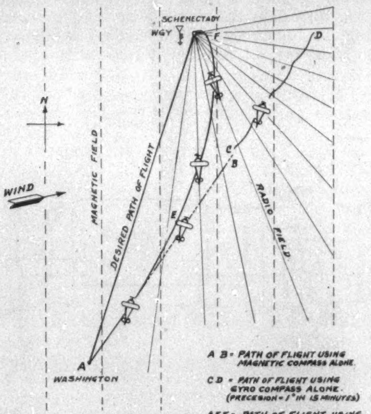
SCHENECTADY
WGY
F
D
N
WIND
MAGNETIC FIELD
DESIRED PATH OF FLIGHT
RADIO FIELD
C
B
E
A
WASHINGTON
A B = PATH OF FLIGHT USING MAGNETIC COMPASS ALONE.
C D = PATH OF FLIGHT USING GYRO COMPASS ALONE. (PRECESSION = 1° IN 15 MINUTES)
AEF = PATH OF FLIGHT USING RADIO COMPASS ALONE.

FIG. 3—DIAGRAM SHOWING DRIFT OF AN AIRPLANE FROM A STRAIGHT LINE COURSE CAUSED BY WIND

Receivers equipped with automatic volume control can be used with this compass because such control not only automatically increases the amplitude of the combined signal from the radio loop and vertical antenna, but also maintains the ratio between the $f$ and $2f$ frequency in the audio output circuit. Referring to Fig. 1 it may be noted that the average values of the radio frequency current when the loop voltage adds to that from the antenna (Fig. 1*D* and *F*) is higher than when it opposes (Fig. 1*E* and *G*). This causes a shift in the operating level at the detector tube and if, when using automatic volume control, an attempt is made to operate on too powerful a signal, erratic results will be obtained. This can be compensated partially by varying the respective pick-up between the loop and antenna. It is experienced only when approaching a powerful transmitting antenna and generally is not required with a hand operated volume control.

The audio frequency required to modulate the loop output can be of any value that will pass through the receiver without too much distortion. There are two factors which govern the frequency: if the frequency is higher than 1,500 cycles, a high-pass filter can be used to limit voice effects from appearing on the indicator; because the modulating frequency is made up of a fundamental and second harmonic, the receiver should be capable of handling the second harmonic frequency without too much transmission loss, otherwise the sensitivity will be affected. It also may be desirable to keep the frequency fairly high in order to use the lower range for continuous wave telegraph reception.

The sensitivity around the zero point depends on the type of signal being received. On unmodulated continuous wave stations it is a maximum, and on badly overmodulated waves a minimum, averaging approximately 10 deg for full scale deflection daylight reception on broadcast stations 150 miles away. By using head phones directions can be obtained down to a fraction of a degree.

The distance range of the compass attachment is limited to that of the radio receiver with which it is operated; in general it will give satisfactory bearings on broadcast stations that can be received loud enough for ordinary loud-speaker operation or, in reception on aircraft, the range is about the same as that obtainable for head phone reception. Rough bearings can be obtained in bad static conditions when telephone reception is impractical.

With a satisfactory radio compass it becomes possible to navigate an aircraft with much greater accuracy, with a resultant saving in fuel; it permits night expeditions over strange territory or water; it is valuable in photographing; when one is lost it becomes useful in obtaining angles for triangulation; and when combined with a magnetic compass it presents a system of navigation which automatically corrects for wind drift.

## COMBINATION OF RADIO COMPASS AND MAGNETIC COMPASS

Referring to Fig. 3, if one wishes to fly from Washington, D. C., to Schenectady, N. Y., and maintain his course by following a magnetic compass with a west wind blowing he would travel a course

*AB* to the east, never arriving in Schenectady. If he tuned in radio station WGY and flew according to the radio compass the course would be along *AEF* eventually arriving but traveling a considerable distance out of his way. Referring to Fig. 4 it may be noted that angle *a* between the magnetic north and the course remains constant whereas if the craft should drift to the left, for instance, it might still be headed for its destination by following the radio compass but the angle with respect to the north pole would become *b*. Thus in order to maintain both the magnetic angle and the radio compass satisfied, it is necessary to keep on a straight line course to the destination.

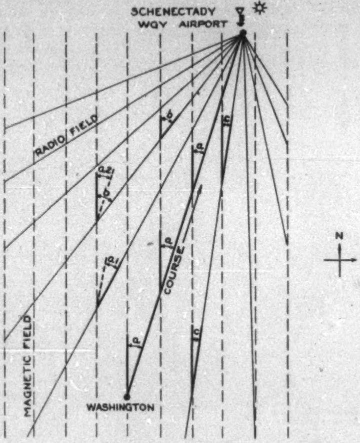

Fig. 4—Diagram Showing How an Airplane Is Held to Its Course by Combining Radio, Magnetic, and Gyro Units in a Compass System

The following system to accomplish correction for drift will operate with any type of compass, but tests have been made with the magneto compass, hence a brief description of this instrument is given. It is essentially a small d-c generator (Fig. 5) which depends on the earth's magnetic field for excitation and obtains its rotating power either from a 12-volt motor or a wind driven impeller. In order to collect a maximum of magnetic flux for the field, permalloy poles are used. A sensitive center-scale ammeter is used for the indicator and the indication becomes zero when the poles are in the east-west position. The instant the poles are turned away from this position a magnetic field is established across the armature causing a voltage to be generated and an indication on the indicator, the direction depending upon which way the flux travels through the poles.

There is a remote control or course-setter which enables the poles to be rotated to a position which will be east and west when the aircraft is on its proper course. The output of the compass generator also can be used to operate a sensitive polarized relay which in turn can be used to operate an automatic steering engine, Fig. 6. This engine is driven by a 12-volt motor which rotates the steering drum in either direction by the use of electrically operated clutches. The clutches are controlled by the magneto compass and the overall system is stabilized by a follow-up system which introduces a counter emf in the compass circuit eventually becoming equal and opposite in polarity to the current generated by the compass. The follow-up device is operated directly from the steering drum and permits the rudder to be turned an amount proportional to the current from the compass. It also causes the rudder to return to its mid-position without overshooting.

Referring to Fig. 7 it may be noted that in order to maintain a straight course between the starting point and the destination, it is necessary to maintain the radio compass loop $L_1$ $L_2$ normal to the course and the magnetic compass poles $P_1$ $P_2$ east and west. If the aircraft be permitted to drift to position *B* and the angles of both compasses are not changed, then it may be seen that the radio loop is no longer normal to the radio station or course; and if the output of the radio compass was used to control the rudder, the craft would make a left turn toward the straight line course.

In order to make this correction automatic it is necessary to operate the compass pole rotating mechanism with a motor and also to permit the loop to be rotated. Figure 8 shows a test stand equipped with the developmental equipment. The steering engine here differs somewhat from the one previously shown in that it contains an extra set of clutches and a differential gear box, the drum on top of the engine

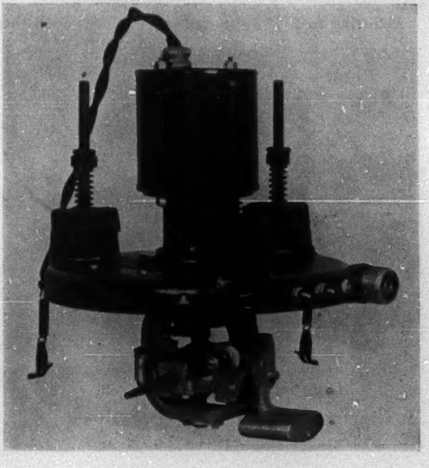

Fig. 5—A Motor Driven Magneto Compass Generator With Cover Removed

having a small metal rudder which represents the rudder of an aircraft. The control panel is arranged so that the rudder can be operated directly by either the magneto compass, the radio compass, or the combination of the two which gives automatic drift correction. When switched for drift correction the magneto compass poles are automatically kept in an east-west position by using the output of the compass to control the second clutch assembly; this in turn rotates the poles until the compass output is zero. Attached to this clutch mechanism is a differential gear box which is connected mechanically to the rotating mechanism of the radio loop. The differential gear box permits the angle between the radio compass and the magneto compass to be set and after that no matter which way the aircraft is turned the two compasses will remain at a fixed angle with respect to the magnetic north pole.

The output of the radio compass controls the rudder and thus the craft is directed according to the angle set up between the two compasses. To correct for wind effects the craft will automatically assume a heading or "crab" into the wind a sufficient amount to maintain its course on a straight line. If the wind increases or decreases the "crabbing" angle will automatically change.

The gyro turn compensator is used to stabilize the system in rough weather and when making rapid turns, although the equipment is intended for use only for fairly long level flights and not for rapid maneuvers.

Referring to Fig. 8 showing the control panel, the course setter to the right is used to set the angle of the course and the indicator to the left shows the actual heading of the aircraft. By subtracting the two angles the difference indicates the angle of crab and is a direct indication of the effect of the wind.

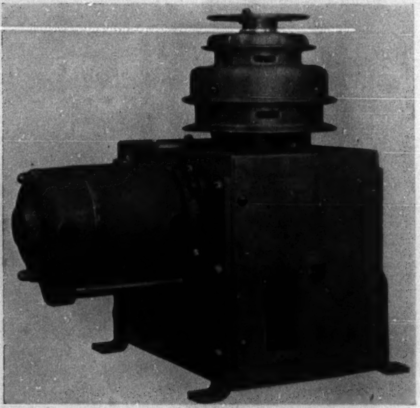

Fig. 6—Developmental Aircraft Rudder Engine for Automatic Steering, With Dynamotor

After establishing the ability of maintaining a straight course and the angle of crab, it remains necessary only to determine ground speed to determine the exact location during the flight. This may be determined by orienting the loop on a second radio transmitting station.

Using test equipment a plane has been automatically steered to destination with correction for drift by the described method, but work remains to be done to reduce the equipment to service form.

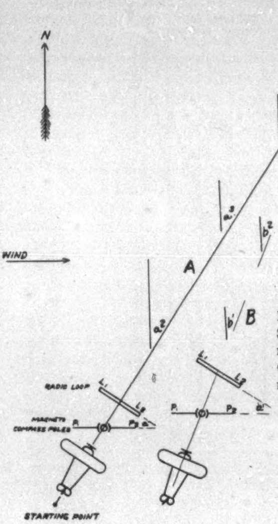

Fig. 7—Diagram Showing How an Airplane Is Held to Its Course by a Combined Radio and Magnetic Compass

## Landing Aids

The safe landing of aircraft during adverse weather conditions remains the great problem confronting air transportation. In general, transport companies avoid any possibility of being caught in a position where it is necessary to attempt a landing in fog, in the same way that all ocean liners meet their corresponding problem. However, several organizations are now making strenuous efforts to solve this problem. Here it is that all the agencies are to be investigated, radio, sound, light, and any others, for each may contribute to the solution.

The landing of planes at an airport under blind flight conditions requires the guidance of the plane from the beacon course or the course determined by radio compass to an approach course at the airport, the determination of runway position, knowledge of height above ground and traffic conditions about the port.

Several methods have been proposed and demonstrated, including the Guggenheim Fund work of Major Doolittle, the short-wave radio beam developed by the Aeronautics Research Division of the

Department of Commerce at the U.S. Bureau of Standards, the system developed at Wright Field by Captain Hegenberger, and others. As in other flight equipment, it is desirable to limit the total apparatus, particularly that on the plane, to a minimum, and to make use as far as possible of instruments that are needed for normal flights or that become an aid in emergency landings. Thus the relocation of those range beacon transmitters situated near an airport such that one of the radiating courses lies across the airport as now planned by the airways division will assist the pilot, and the use of available receiving equipment aboard the plane without duplication serves to reduce the carried weight to a minimum.

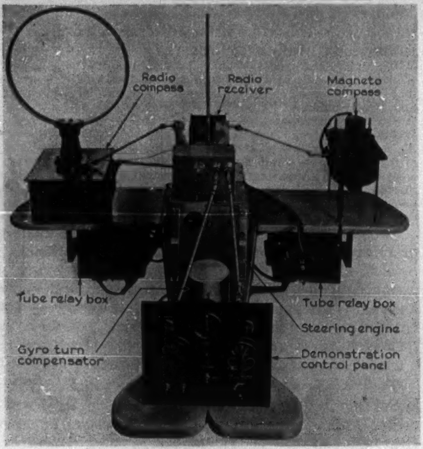

Fig. 8—Experimental Automatic Steering Control With Automatic Radio Drift Correction, Mounted on a Test Stand

A few portable runway-localizing beacons have been constructed which have outputs of from 10 to 15 watts. These use small cross loop antennas so located that the vertical plane containing the axis of the desired runway bisects the angle between the two loops. These beacons are essentially the same as the radio range beacons mentioned previously except smaller in size and output.

The range of the localizer transmitters is from 7 to 15 miles so that a plane may be brought in from a distant range beacon course to the desired runway. It is desirable that the set be adapted to voice modulation, thus placing the operator in telephone communication with the pilot at any time.

The localizing beacon can be used with several types of supplementary aids. Airport boundary marking may be effected by radio or sonic markers each throwing out a barrage through which the plane, in passing, receives an aural or visual indication. The indication of height above ground may be determined by a sensitive barometric altimeter or by a sonic altimeter. The first gives approximate comparative heights which do not follow the contour of the terrain while the sonic altimeter, described elsewhere,[6,7] permits the pilot to know his height during the glide over adjacent ground, the time at which he passes the boundary, providing the sonic type of boundary marker is used, and the gradual approach to the surface of the runway in normal gliding position thus eliminating the necessity for a shock landing. The sonic altimeter likewise is effective in emergency landings.

It is not yet apparent what the ultimate system or systems will be, but whatever leads to successful operation will lean heavily upon radio aids. Tests conducted to date with the equipment described in this paper show results indicative of material aid in the solution of problems of flight.

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## Discussion

For discussion of this paper see page 736.

# Reactive Power Concepts in Need of Clarification

BY ARCHER E. KNOWLTON*

Fellow A.I.E.E.

***Synopsis.**—To assist in clarifying the present concepts of reactive power, the following introduction to the subject has been prepared. An analysis of the reactive conventions made by Doctor Silsbee, a member of the subcommittee, is included.*

IF ALL electrical iron could by divine decree or presidential proclamation be straightened into uniform permeability over its whole range of magnetization there would be less occasion to raise the question of adequacy of our prevailing concepts of reactive power and power factor. If all synchronous machine windings under all conditions of loading could have flux distribution in strict conformity with symmetrical sinusoidal generation there would be still less. Moreover, the excuse would nearly vanish if polyphase circuits could always be held to rigid balance of impedances on their lines and loads. With these factors eliminated the residue of doubt, if any, would be a topic to intrigue only the academic and metaphysical minds.

But no one of these 3 ideals is attained fully in practice and the degree of departure in any particular instance is what justifies an effort to take some of the slack out of the power factor and reactive concepts. However, power factor is only a ratio expressing the interrelations between true power, apparent power, and reactive power. The focus is at once upon reactive power because of the 3 aspects of energy flow, it has been given second place in analysis and measurement.

The quadrature component accompanying energy flow in inductive and capacitive circuits has vagaries which, relatively speaking, have been overlooked while energy, power, voltage, and current were being explored and reduced to systematic and conventional procedure. During the last 5 years there has been a growing disposition in academic circles to turn the mathematical weapons concertedly upon the reactive constituent. To Prof. Constantin D. Busila of the Polytechnic School at Bucharest, Roumania, and Roumanian representative on the International Electrotechnical Commission, is given most of the credit for bringing the loose status of flux-energy to the fore. At the International Conference on High-Voltage Electric Systems (Paris, 1927), Professor Busila presented a paper, "The Power Factor and Its Improvement." Discussion of it disclosed such differences of opinion on the basic phenomena that a special advisory committee was formed under Roumanian sponsorship. Out of it came the Roumanian "Questionnaire on the Problem of Reactive Power" which was given international circulation.

No categorical answer to that questionnaire has been given by the A.I.E.E. A special subcommittee* was constituted by the standards committee to prepare an answer. In 1931 the only answer that could even partially be agreed upon as a suggestion to the standards committee for transmission to the Roumanian committee was that:

> "... prevailing methods of measuring reactive components are acceptable as a practical expediency, although it is recognized that errors of measurement are incurred under unbalanced and non-sinusoidal conditions. However, the relative unimportance, from the economic standpoint, of reactive power flow as compared with demand and energy elements of electricity costs tends to discount the value of an exhaustive and abstract analysis of the inconsistencies of reactive concepts and the corresponding technique of measurement. In brief, American practice is content with the definition of reactive component as that quantity which is measured when the potential is shifted to quadrature with its appropriate vector position for true power measurement.

Such an answer at the most appears to be evasive or temporary and not erudite or graced with much professional courtesy. The committee set about assembling the foundation for a more comprehensive answer. The symposium on reactive power at the Institute's North Eastern District meeting in Schenectady, May 10–12, 1933, is one result and is a major phase of the subcommittee's activity.

That is the history. Now why so much concern about a circuit manifestation that is always subordinate to the energy and power objectives of practical operation? It is condoned and tolerated, manipulated subserviently, by some viewed merely as the source of power-factor characteristics, by others as merely something to be metered as simply as possible. But the Institute owes to the profession the reduction of the quadrature component to the same degree of specificity as has been done with the true power and energy. Otherwise there can be no rigid definition of power factor (we have one now but it is admittedly not the whole and final answer). In fact the whole uncertainty about reactive power could readily be exaggerated to the point where power factor would have to sacrifice its present abode among the élite definitions (like those of energy, potential, capacitance, etc.) and move into a more plebeian neighborhood (among diversity factor, load factor, use factor, etc.). Some of the queries raised about the quadrature component must, unless it is reduced to systematic treatment, lead to that result for all persons who think occasionally of circuits other than those permanently balanced and subjected only to sinusoidal currents and sinusoidal voltages.

Energy in transit in an electrical system can perhaps be likened to an army on the march over varied terrain. The ideal would be an accelerated and synchronized movement of all branches up to noon and a decelerated movement toward nightfall and encampment—smooth progress "all above the line" like the instantaneous progress of energy in a non-reactive circuit. But actually the tired and ponderous units "lag" and delay the procession when the going meets obstacles. Light and eager units "lead" the rush when there are vacant and alluring tarrying points ahead. Most of the army ultimately gets to its destination and is potentially useful on arrival but the route and the terminal bring out the mobility idiosyncrasies of heavy tanks and fast motor units, speedy cavalry, and sluggish infantry. The laws of the mass movement are relatively simple but the laws of the out-of-phase movements are a bit intricate. Inject the rearward movement of units back to the base for refreshment and recoupment and the picture becomes more complete and more intricate. What is the "power factor" of such a system? What would it be for a complete military force embracing 3 armies moving in parallel to a common objective?

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*Chairman, A.I.E.E. Subcommittee on Reactive Power.

This article serves as an introduction to the reactive power symposium held during the Institute's North Eastern District Meeting, Schenectady, N. Y., May 10–12, 1933.

* Subcommittee on reactive power: Vannevar Bush, A. L. Cook, W. B. Kouwenhoven, F. A. Laws, P. MacGahan, F. V. Magalhaes, E. J. Rutan, F. B. Silsbee, and A. E. Knowlton, *chairman.*

To make the presentation more specific in electrotechnical terms here are a few of the vagaries, occasionally stated categorically but in fact subject to argument and, at present, opinion. The author disclaims any intention to take sides on any point. The intent of this introduction and of the Schenectady symposium is to elicit all viewpoints with the hope of clarifying the issue and making progress toward conventional handling of the concepts, the terminology, the symbolism, the metering, and the economic application of the reactive component of energy flow. The following are largely paraphrased from the Roumanian Questionnaire.

1. Reactive power is not conserved in exchanges between circuits of different frequency (rotor and stator of induction motor, for example.)

2. Reactive power to some may present a paradoxical tendency to change sign when the phase-sequence or alternator rotation is reversed.

3. For some, reactive power is distinct from the mean intrinsic energy localized in the electric and magnetic flux fields.

4. Some apparently attribute to reactive power only that degree of reality that attends the circulation or oscillation of intrinsic energy between the reactive receiving devices and the transmitting network.

5. Since (4) leads to a mean value of zero for the instantaneous condition of the interchanges, some hold that reactive power is wholly fictitious and has no reality.

6. Even though the accepted labelling of reactive power as $V \sin \varphi$ is identical with $2\omega(W_L - W_C)$, that is, twice $2\pi f$ times the net difference between instantaneous magnetic and electrostatic energies, for sinusoidal conditions, what will be taken for $f$ where non-sinusoidal conditions arise from a superposition of frequencies?

7. The preceding items indicate the necessity of establishing the degrees of reality and fictitiousness which shall be assigned to reactive power.

8. Until this is done there remains an element of uncertainty in the following commonplace relationships for all but the ideal transfers of energy in which volts, amperes, and watts hold to strictly sinusoidal behavior:

$$\begin{aligned} P &= EI \cos \varphi \\ Q &= EI \sin \varphi \\ EI &= \sqrt{P^2 + Q^2} \end{aligned}$$

9. With equal doubt therefore about $Q$ and $\varphi$ there is a geometrical uncertainty in the vector diagrams which represent the effective values of non-sinusoidal quantities or the single-phase equivalents of unbalanced polyphase quantities. The conventional way of finding the sinusoidal equivalent of non-sinusoidal quantities meets the requirements of true power but introduces inconsistencies with regard to the out-of-phase manifestations.

10. The rising reversion to d-c by way of rectification devices brings non-sinusoidal manifestation to the fore and thus accentuates the need for elevating reactive concepts toward parity with the true-power concepts.

11. Substitution of equivalent sinusoids suffices for power treatment but, since the proportioning of the harmonics affects the reactive quantity, the equivalent sinusoids are not wholly determinative for the reactive quantity.

12. Reciprocal deformation effects between current and voltage occasion cross-product terms in the expansion of a power expression which cancel in the final summation for delivered power but they do not cancel correspondingly in the reactive expression.

13. It appears that a deformation factor may be needed to rid the reactive component of its uncertainty under non-sinusoidal conditions or else a term for "deformation power" introduced as a correction. One suggestion (Liénard) has been that "apparent power is equal to the maximum of the values which the active power can take when we modify in all possible manners the form of the current and that of the applied voltage, the effective values of these voltages and currents remaining fixed."

14. In some quarters "reactive factor" (reactive power divided by real power) is coming into use and approaching sanction. It will inherit the same weakness as power factor.

Those are the elements of the problem. The incidence of these areas of doubtful status upon the electric system seems to fall primarily into certain categories. First, there is the mathematical approach to ascertain the degree of reality to be assigned to the quadrature component. This is treated from the abstract point of view by Professor W. V. Lyon in his paper, "Reactive Power and Power-Factor." Second, there is the analysis of the non-conservative attribute of reactive power when viewed from the standpoint of the mesh which constitutes the practical system of power transmission; Professor V. G. Smith's paper, "Reactive and Fictitious Power," is on this topic. Third, the technique of symmetrical coördinates could well be applied to this subject to ascertain how much conversion to balanced systems would be helpful in reducing the uncertainties; this C. L. Fortescue has done in his paper, "Power, Reactive Volt-Amperes, Power-Factor." Fourth, power system operators have come to look upon the reactive component as a quantity to be dispatched more or less independently of the true power. About it has grown a technique which should be correlated with the academic analysis; one practice in this respect is presented by J. A. Johnson in his paper, "Operating Aspects of Reactive Power." Fifth, the meter technician has a point of view on this matter because in the final analysis it is his task to meter reactive component in conformity with the standards and conventions. W. H. Pratt expresses this point of view in his paper, "Notes on the Measurement of Reactive Volt-Amperes."

More or less distinct from the foregoing is a call to establish a conventional procedure in representing the reactive component in power triangles. Practice is about evenly divided. Some engineers and writers habitually or advisedly draw lagging reactive component vertically upward and some draw it downward from the right-hand end of the kilowatt base. A leading component is of course given the reverse direction by the 2 schools of thought and practice. Misinterpretation is manifestly possible under such divergent practice where the author assumes that the reader belongs to his own camp and therefore fails to label his diagrams specifically.

This confusion was referred to the subcommittee by the standards committee so that the United States national committee of the International Electrotechnical Commission may be enabled to recommend through Prof. A. E. Kennelly to the committee on electromagnetic and magnetic units, the conventional treatment preferred by the A.I.E.E. A ballot mailed to 75 actively interested members of the Institute brought response from 50 but there was not a strong preponderance for either standard. The most comprehensive reply was submitted by Dr. F. B. Silsbee, a member of the subcommittee. He advocates standardizing inductive kilovars as positive and capacitive kilovars as negative in power triangles.

With no intention of influencing any one who may wish to contribute his preference for the committee's guidance but merely because it displays admirably the factors upon which a decision could be based on analytical grounds as contrasted with the habitual, the presentation of Dr. Silsbee is incorporated herewith. The committee will welcome letters from Institute members who read this and, because of it or in spite of it, hope to see a particular geometrical direction assigned to reactive power of the inductive and capacitive forms when represented with power and volt-amperes in power triangles. Dr. Silsbee's presentation follows:

## ALTERNATIVE PROCESSES FOR DEFINING THE SIGN OF REACTIVE VOLT-AMPERES

The following general principles may be set up as governing the adoption of scientific conventions as to the signs of electrical quantities:

1. Positive real quantities are drawn to the right, and positive imaginary quantities are drawn upward.

2. A resultant effect is the (complex) sum of its components. Thus if $c$ is the resultant of $a$ and $jb$, we write $c = a + jb$ and draw $b$ upward.

3. By the rules of complex algebra $d$, the reciprocal of $c$ is given by

$$d = \frac{1}{c} = \frac{1}{a + jb} = \frac{a}{a^2 + b^2} - \frac{jb}{a^2 + b^2}$$

4. The unnecessary introduction of negatives in fundamental definitions is to be avoided.

Of the foregoing statements, 1, 2, and 3 are part of our fundamental mathematical notation and are now so universally accepted as to stand unchallenged. Statement 4 is a more philosophical point but of generally recognized weight.

Confining our attention to sinusoidal current $I$ and voltage $E$ we have

5. $R = P/I^2$, $P$ being the real power.

6. $X = \omega L - \frac{}{\omega C}$

7. $Z = R + jX.$

8. The phase angle of the impedance is $\theta_z = \tan^{-1}\frac{X}{R}.$

The sign of $X$ is the result of a purely arbitrary choice, made so long ago that there seems little need, or hope, of changing it. Eq 7 indicates that impedance is the resultant of resistance and reactance in the sense of principle 2.

We also have the definition

9. $Y = \frac{1}{Z}$

which by principle 3 leads to

10. $Y = \frac{R}{Z^2} - \frac{jX}{Z^2}$

and as an abbreviation we define the conductance

11. $G = \frac{R}{Z^2}$

All of the relations to this point follow from the arbitrary principle 6, with no violation of any of the first 4 principles. In the definitions of susceptance, $B$, however, 2 alternatives present themselves. One of these, which is that generally used (certainly in the United States) will be designated in Table I as **I**; while the opposite, which will be designated by **II**, has been urged by some. The inherent difficulty from the minus sign in 3 is met in a different fashion in the 2 conventions and neither is all that could be desired.

Of the alternatives in Table I it will be seen that **IBa** is the only.

**Table I—Alternative Conventions**

<table>
<tr><td colspan="4">I*</td><td colspan="4">II*</td></tr>
<tr><td colspan="4">12. $B = +\frac{X}{Z^2}$<br>Thus satisfying 4<br>Whence<br>13. $Y = G - jB$<br>violating 2; or stating that $Y$ is not the resultant of $G$ and $B$.<br>The phase angle of admittance is<br>14. $\theta_Y = \tan^{-1}\frac{(-B)}{G} = -\theta_Z$</td><td colspan="4">$B = -\frac{X}{Z^2}$<br>violating 4<br>Whence<br>13. $Y = G + jB$<br>thus satisfying 2<br>The phase angle of admittance is<br>14. $\theta_Y = \tan^{-1}\frac{+B}{G} = -\theta_Z$</td></tr>
<tr><td colspan="2">IA</td><td colspan="2">IB</td><td colspan="2">IIA</td><td colspan="2">IIB</td></tr>
<tr><td colspan="2">15. $Q = -I^2X$<br>16. $= -E^2B$<br>17. $= +EI \sin\theta_Y$</td><td colspan="2">$Q = +I^2X$<br>$= +E^2B$<br>$= +EI \sin\theta_Z$</td><td colspan="2">$Q = -I^2X$<br>$= +E^2B$<br>$= +EI \sin\theta_Y$</td><td colspan="2">$Q = +I^2X$<br>$= -E^2B$<br>$= +EI \sin\theta_Z$</td></tr>
<tr><td>IAa</td><td>IAb</td><td>IBa</td><td>IBb</td><td>IIAa</td><td>IIAb</td><td>IIBa</td><td>IIBb</td></tr>
<tr><td>18. $V = P + jQ$</td><td>$V = P - jQ$</td><td>$V = P + jQ$</td><td>$V = P - jQ$</td><td>$V = P - jQ$</td><td>$V = P - jQ$</td><td>$V = P + jQ$</td><td>$V = P - jQ$</td></tr>
<tr><td colspan="8">*For a circuit in which inductance predominates Q will be drawn*</td></tr>
<tr><td>19. down</td><td>up</td><td>up</td><td>down</td><td>down</td><td>up</td><td>up</td><td>down</td></tr>
</table>

*For either of these conventions, the reactive volt-amperes $Q$ may conceivably be defined as either + or −, thus giving 4 alternatives, and (if a further violation of principle 2 is invoked) each of these 4 alternatives gives rise to 2 ways of drawing the power triangle; i. e., as $V = P + jQ$ or as $V = P - jQ$. The resulting 8 procedures are here shown in tabular form.

one which does not involve at least one violation of principle 2 or 4 in addition to the unavoidable violation at step 12 or 13 which occurs in all procedures. Alternatives **IIA** and **IIB** both suffer from the inconvenient change in form (though not in substance) according as $Q$ is defined from $X$ or from $B$.

The drawing of the power vector parallel to the current vector (down in the inductive case) is attained in **IAa, IBb, IIAa** and **IIAb.**

In addition to the formal principles listed above consideration should also be given to the following facts:

20. The almost universal use of constant voltage systems for the transmission and utilization of electric power makes the calculation of circuits by using their admittance, conductance, and susceptance the most logical and direct.

21. Habits of thought arising by the historical accident that series circuits were first studied theoretically make the average engineer more familiar with the quantities impedance, resistance, and reactance.

22. The use of reactive power as equivalent to $2\omega(W_m - W_e)$ where $W_m$ and $W_e$ are the magnetic and electrostatic energies, has already come into considerable use in the literature.

## Discussion

For discussion of this paper see page 779.

# Reactive and Fictitious Power

BY V. G. SMITH*
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***Synopsis.**—In this paper the single-phase and polyphase definitions of reactive power are considered. The single-phase definition is unsatisfactory when the current and voltage wave forms are complex. The polyphase definition is the better but requires the independent recognition of the effects of distortion and, in the case of four or more wires, mesh distribution. The geometric difference between the apparent power and the power may be called the fictitious power to distinguish it from the reactive power which is only part of the fictitious power.*

THE conception of reactive power originated in the single-phase sinusoidal problem. In attempting to extend the idea to complex waves and multiple phases, certain difficulties arise which are well worth investigation.

## SINGLE-PHASE

In the A.I.E.E. rules there are 2 definitions of reactive power, $\pm\sqrt{E^2I^2 - P^2}$ for single-phase and $\Sigma E_nI_n \sin \theta_n$ for polyphase circuits, the summation extending over all harmonics and all phases. Applied to single-phase cases they cannot be reconciled except for sine waves or a load of pure resistance or its equivalent.

It may be shown[1] (for references see list at end of paper) that

$$E^2I^2 - P^2 = \{\Sigma E_nI_n \sin \theta_n\}^2 + [\Sigma\{E^2{}_mI^2{}_n - 2E_mE_nI_mI_n \cos(\theta_m - \theta_n) + E^2{}_nI^2{}_m\}] = P^2{}_r + P^2{}_d \qquad (1)$$

where $P_r$ is the reactive power by the polyphase definition and $P_d$ is the square root of the fourth term. This fourth term will vanish if the circuit presents the same impedance to all harmonics, i. e., if

$$\theta_m = \theta_n \text{ and } E_m/I_m = E_n/I_n \qquad (2)$$

This quantity is due therefore to the distorting effect of the circuit and $P_d$ may be called the "distortion" power. (In the Roumanian Questionnaire[2] it is called the "deforming" power but the word "distortion" is already well established in communication literature.) The relations between these quantities are shown in Fig. 1.

## ALGEBRAIC SIGNS

The idea of an algebraic sign is natural for sine waves and it is best to define leading reactive power as positive. Now the quantity $\pm\sqrt{E^2I^2 - P^2}$ may exist when there is no lead or lag but merely distortion.[3] In such cases which sign shall be used? On the other hand the quantity $\Sigma E_nI_n \sin \theta_n$ has a definite algebraic sign depending upon the sinusoidal definition. Budeanu has called $P_f = \sqrt{E^2I^2 - P^2}$ the fictitious power. Apparently $P_d$ and $P_f$ may be taken as positive, no significance being attached to a negative sign.

The case of a sinusoidal voltage applied to a cyclically variable resistance is often quoted to show that $\sqrt{E^2I^2 - P^2}$ may exist when there is no electromagnetic energy storage, but it should be pointed out that $P_r = \Sigma E_nI_n \sin \theta_n$ may also exist under the same conditions if the resistance cycle is unsymmetrical with respect to the voltage maximum. This would occur where there was heat storage. The reactive power $P_r$ therefore is, in the most general case, an abstract mathematical quantity. [1] (When an opinion is expressed concerning one of the questions in the Roumanian Questionnaire the number of the question is given in square brackets.)

In spite of the fact that distortion and electromagnetic energy storage are inextricably mixed in the most general case, $P_r = \Sigma E_nI_n \sin \theta_n$ is the best definition of reactive power yet proposed. It forms a symmetrical pair with $P = \Sigma E_nI_n \cos \theta_n$, reduces correctly to the sinusoidal form in all cases, and determines the algebraic sign. Thus the reactive power of a neon sign with a resistor ballast is zero but the distortion power is not. As the phenomenon is really distortion it is surely better so to describe it. [9]

## POLYPHASE CIRCUITS

The reactive power $P_r = \Sigma E_nI_n \sin \theta_n$, has an immediate meaning in a polyphase circuit. The order of summation, over phases or harmonics, and the point to which the potential differences are measured, are immaterial. However, it does not give complete information about the system.

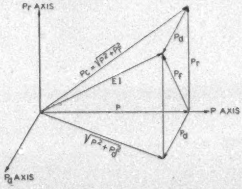

FIG. 1—VECTOR RELATION BETWEEN POWER, REACTIVE POWER, FICTITIOUS POWER, DISTORTION POWER, AND COMBINED POWER IN A SINGLE-PHASE CIRCUIT

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*Presented at the North Eastern District Meeting of the A.I.E.E., Schenectady, N. Y., May 10–12, 1933.*

Fortescue[4] has suggested a definition based on symmetrical components but it is limited to sine waves and is too special to serve as a general definition. The fictitious power in polyphase circuits may be defined as $P_f = \sqrt{P^2_{ap} - P^2}$, where $P_{ap}$ is the apparent power. The only satisfactory definition of the apparent power is that of Lyon[5] and Liénard.[3] It is the maximum power obtainable when the phases and wave forms of the currents and voltages are varied in every possible manner consistent with Kirchhoff's laws, the effective values remaining constant.

### POLYPHASE CIRCUITS WITH SINE WAVES

The reactive power $P_r = \Sigma E_n I_n \sin \theta_n$, is the natural definition with sine waves and is the one always used. It makes $P_r$ the algebraic sum of the reactive powers of the load elements. Fictitious power can occur even with sine waves if the circuit is of 4 or more wires. This includes the case of the 3-phase 4-wire circuit.

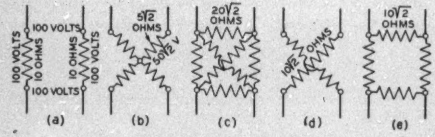

FIG. 2—AN EXAMPLE OF FICTITIOUS POWER IN A TWO-PHASE FOUR-WIRE MESH CIRCUIT

It is shown in Appendix I that the stationary values of the power occur when each line current is in phase with or in opposition to the voltage from the corresponding line to some common point. Among these stationary values is the greatest power, $P_{ap}$.

The simplest type of load to meet these requirements is a star of positive and negative resistances with the neutral point as the common point in question. If it is possible to secure the given root mean square line currents by means of a star of all positive resistances, that star is unique and takes the greatest possible power, $P_{ap}$. Sometimes, however, it is necessary to introduce 1 or 2 negative resistances.

A mesh of pure resistances will not in general be such as to cause the line currents to be in phase with or opposed to the voltages to some common point. Consequently the power is less than $P_{ap}$ and fictitious power,

$$P_f = \sqrt{P_{ap}{}^2 - P^2} \tag{3}$$

exists. It is not due to energy storage or distortion but to the distribution of the elements of the mesh and may be called the "fictitious mesh power." Meshes which are equivalent to some pure resistance star will not show fictitious power. Other meshes may show fictitious power on one voltage system and not on another.

A simple example in a 2-phase 4-wire circuit is shown in Fig. 2. Let (*a*) be the actual load and (*b*) the star which takes the same line currents. Both take 10 amp per line but in (*a*) the power is only 2 kw while in (*b*) it is $2\sqrt{2}$ kw. The fictitious mesh power of (*a*) is $\sqrt{(2\sqrt{2})^2 - 2^2} = 2$ kw. Circuit (*c*) is the mesh equivalent to (*b*) while (*d*) and (*e*) take the same power as (*b*) on the balanced voltages but would not in general take the same power.

In the case of 3 wires the mesh is a delta which may be reduced to a wye. A pure resistance delta can show no fictitious mesh power. In fact, it may be shown that the power is a maximum when the total reactive power is zero whether the load is a pure resistance or not and that the 3 line currents are then in phase with the voltages to a common point. The maximum power $P_{ap}$ is $\sqrt{P^2 + P_r^2}$, for 3 wires, sine waves, and there is no such thing as fictitious mesh power in this case.

### POLYPHASE CIRCUITS WITH COMPLEX WAVES

It is shown in Appendix II that the resistance star is the type of load which absorbs the greatest power when the wave forms are complex. In some cases 1 or 2 negative resistances may be necessary. All that has been said concerning meshes and fictitious mesh power in the sinusoidal case applies equally well here. The 3-wire case is again special and will not show fictitious mesh power. When the mesh is not formed of pure resistances the distortion and mesh parts of the fictitious power are inextricably combined.

### MEASUREMENTS

The measurement of $\sqrt{E^2 I^2 - P^2}$ directly would be very difficult but each quantity in it may be measured with considerable accuracy. The measurement of $\Sigma E_n I_n \sin \theta_n$ is theoretically possible by means of a series of perfect filters, provided the frequency were absolutely constant. In practice, the voltages are usually nearly enough sinusoidal and balanced that the method of applying a quadrature voltage to a wattmeter is sufficiently accurate. If the voltages are sinusoidal and balanced the wave forms and unbalance of the currents do not matter provided proper methods are used. No direct method of measuring the apparent power or the fictitious power in a polyphase network is known. The currents, voltages, and power may be measured and in some cases the apparent and fictitious powers calculated from them.

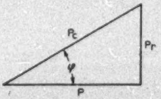

FIG. 3—RIGHT-ANGLED TRIANGLE CONNECTING $P$ $P_r$ AND $P_c$. IN THE PROPOSED DEFINITION $P_c$ WOULD NOT EQUAL $VI$ AND THE ANGLE $\varphi$ WOULD HAVE NO MEANING APART FROM THE TRIANGLE

## CONCLUSIONS AND SUGGESTIONS

The existing definition of reactive power in a single-phase circuit, $\pm\sqrt{E^2I^2 - P^2}$, leads to an unsatisfactory situation when the waves are complex. Any attempt to extend it in the form $\pm\sqrt{P^2_{ap} - P^2}$ to polyphase circuits leads to the conclusion that a pure resistance mesh must be considered to cause reactive power. This rules out the wattmeter method of measurement and provides no other in its place, a procedure to which metermen would strenuously object. Of course this is due to the Lyon-Liénard definition of apparent power, but what other definition is possible?

In spite of the difficulties of measurement the definition $P_r = \Sigma E_n I_n \sin\theta_n$ is much the better even for single-phase circuits. Distortion power and fictitious mesh power increase the losses the same as reactive power. If the polyphase definition is to be used it is necessary to recognize the effects of distortion and, in the 4-wire circuit, mesh distribution. [8.]

It is perhaps well to point out that the adoption of this definition will not increase the difficulties of measurement. Distortion and fictitious mesh power are there now but are neglected by the measuring apparatus; the new definitions merely would call attention to their existence.

The following definitions are suggested:

1. Reactive power $P_r = \Sigma E_n I_n \sin\theta_n$ under all conditions. This is the present polyphase definition. [14.]
2. The apparent power $P_{ap}$ is the maximum possible power with the given effective voltages and currents. In the case of a single phase this is $EI$. [10.]
3. The fictitious power is $P_f = \sqrt{P^2_{ap} - P^2}$. [15.]
4. The combined power is $P_e = \sqrt{P^2 + P^2_r}$.
5. The power factor is $P/\sqrt{P^2 + P^2_r} = P/P_e$.
6. The reactive factor is $P_r/P$. This term has another meaning at present but is not much used.[6] [14.]
7. The distortion power in a single-phase circuit is
$P_d = \sqrt{P^2_f - P^2} =$
$\sqrt{\Sigma\{E^2_m I^2_n - 2E_m E_n I_m I_n \cos(\theta_m - \theta_n) + E^2_n I^2_m\}}$.
8. The distortion factor in a single-phase circuit is $P_d/P$.

It does not seem necessary to define fictitious mesh power as it is included in definition 3 of fictitious power.

## ROUMANIAN QUESTIONNAIRE

Comments on some of the questions of the Roumanian Questionnaire[2] follow.

[2]. The form $VI\sin\varphi$ would have to be dropped entirely. A right-angled triangle would still exist connecting $P$, $P_r$ and $P_e$, as in Fig. 3 but the angle $\varphi$ would have no meaning apart from the triangle. The power factor would be $\cos\varphi$ and the reactive factor (new) $\tan\varphi$. [11]. The forms $P = P_e\cos\varphi$ and $P_r = P_e\sin\varphi$ exist but $P_e$ is not $VI$.

[8]. It seems clear that the general case is too complicated to be described completely by the single term "reactive power." Distortion and fictitious mesh power are very difficult to determine and it would be advisable to separate reactive power from them for that reason. In addition there is the advantage of retaining an algebraic sign. [12, 13]. By adopting an algebraic definition of reactive power all need for such terms as "inductive power" and "capacitance power" disappear. The former is negative and the latter positive reactive power.

# Appendix I

### SINE WAVES

The following discussion is limited to 4 wires though it could just as well apply to $n$ wires. The vector notation $\boldsymbol{A}\cdot\boldsymbol{B} = AB\cos\theta$, where $A$ and $B$ are the tensors of $\boldsymbol{A}$ and $\boldsymbol{B}$ and $\theta$ the angle between them, is used.

The total power in a 4-wire circuit may be measured by regarding it as 4 single phases with voltages to any common point. That is

$$P = \sum \boldsymbol{E}_{ro}\cdot\boldsymbol{I}_r = \sum \boldsymbol{E}_{rp}\cdot\boldsymbol{I}_r \tag{4}$$

where $o$ and $p$ are any points, $p$ being thought of as a variable.

Given the effective voltages and line currents, the maximum possible power is required. The voltage system is completely fixed. The variables are the phases of the currents relative to the voltages and subject to the condition $\sum\boldsymbol{I} = 0$

When the currents vary

$$\delta P = \sum \boldsymbol{E}_{rp}\cdot\delta\boldsymbol{I}_r \tag{5}$$

To make the power a maximum this must be zero for all consistent sets of current increments. As in Fig. 4 it is possible to vary any 3 currents and leave the other fixed. Also, since the current magnitudes are given the increments must be at right angles to the currents, i. e.

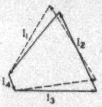

FIG. 4—VARIATION OF LINE CURRENTS

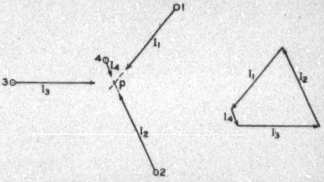

FIG. 5—TOPOGRAPHICAL DIAGRAM

$$\boldsymbol{I}_r\cdot\delta\boldsymbol{I}_r = 0 \tag{6}$$

Now suppose all the voltages are plotted topographically as in Fig. 5, and that all the currents are plotted from their respective wire positions as shown. Let the currents in the lines 1, 2, and $r$ vary ($r$ = 3 or 4), the other being constant, then

$$\delta P = \boldsymbol{E}_{1p}\cdot\delta\boldsymbol{I}_1 + \boldsymbol{E}_{2p}\cdot\delta\boldsymbol{I}_2 + \boldsymbol{E}_{rp}\cdot\delta\boldsymbol{I}_r \tag{7}$$

Now let the point $p$ be chosen at the intersection of the vectors $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ produced. Then $\delta I_1$ is at right angles to $\boldsymbol{E}_{1p}$ and hence

$$\boldsymbol{E}_{1p}\ \delta\boldsymbol{I}_1 = 0 \tag{8}$$

Similarly

$$\boldsymbol{E}_{2_p} \cdot \delta \boldsymbol{I}_2 = 0 \tag{9}$$

Therefore to make $\delta P = 0$ it follows that

$$\boldsymbol{E}_{rp} \cdot \delta \boldsymbol{I}_r = 0 \tag{10}$$

or since $\boldsymbol{I}_r \cdot \delta \boldsymbol{I}_r = 0$, the vector $\boldsymbol{I}_r$ also points directly toward or away from the point $p$.

For a stationary value of the power therefore all currents must be in phase with or opposed to the voltages to some common point. The point must be chosen so that $\sum \boldsymbol{I} = 0$.

## Appendix II

### Complex Waves

The problem is to determine the conditions for maximum power when the waves are complex, given only the effective currents and voltages. For the present suppose that not only are the effective voltages given but also their harmonic components so that the voltage system is completely specified. The line currents may be resolved into harmonic systems quite arbitrarily provided that the vector sum of each harmonic in the 4 lines is zero and that the effective current in each line is as given.

Now suppose that by means of perfect filters each harmonic current system has its own load. Let each of those loads be the star load which gives the greatest power for that harmonic. For any chosen current system this method of loading gives the greatest possible power. It remains to find which of the arbitrary current systems is the best.

Let there be 4 wires and let $\boldsymbol{I}_{ms}$ be the $s^{th}$ harmonic of current in the $m^{th}$ line and let $\boldsymbol{E}_{ms}$ be the $s^{th}$ harmonic of voltage from the $m^{th}$ line to the neutral of the $s^{th}$ harmonic load, then

$$P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} \boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} \tag{11}$$

Also

$$\sum_{m=1}^{4} \boldsymbol{I}_{ms} = 0 \tag{12}$$

by Kirchhoff's first law, and

$$\sum_{s=1}^{\infty} I_{ms}^2 = I_m^2 \tag{13}$$

where $I_m$ is the effective current in the $m^{th}$ line.

When the current system is varied the star loads vary and hence also the voltages to the neutrals. Then,

$$\delta P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} (\boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} + \delta \boldsymbol{E}_{ms} \cdot \boldsymbol{I}_{ms}) \tag{14}$$

$$= \sum_{s=1}^{\infty} (\sum_{m=1}^{4} \boldsymbol{E}_{ms} \enspace \delta \boldsymbol{I}_{ms} + \delta \boldsymbol{E}_{ms} \cdot \sum_{m=1}^{4} \boldsymbol{I}_{ms}) \tag{15}$$

since $\delta \boldsymbol{E}_{ms}$ is common to all 4 lines. By eq 12 the second term of eq 15 is zero, hence

$$\delta P = \sum_{s=1}^{\infty} \sum_{m=1}^{4} \boldsymbol{E}_{ms} \cdot \delta \boldsymbol{I}_{ms} = \sum_{s=1}^{\infty} \sum_{m=1}^{4} r_{ms} \, \boldsymbol{I}_{ms} \cdot \delta \boldsymbol{I}_{ms} \tag{16}$$

$$= \frac{1}{2} \sum_{s=1}^{\infty} \sum_{m=1}^{4} r_{ms} \, \delta \boldsymbol{I}_{ms}^2 \tag{17}$$

where $r_{ms}$ is the resistance of that element of the $s^{th}$ harmonic load which is connected to the $m^{th}$ wire.

Differentiating eq 13

$$\sum_{s=1}^{\infty} \delta I_{ms}^2 = 0 \tag{18}$$

Now it is possible to change the amplitude of any 2 harmonics in the same wire leaving all others constant. The phases of the corresponding harmonics in other wires must be changed but their amplitudes need not. Let only the $s^{th}$ and $t^{th}$ harmonics of current in the $m^{th}$ wire be given increments, then

$$2\delta P = 0 = r_{ms} \, \delta I_{ms}^2 + r_{mt} \, \delta I_{mt}^2 \tag{19}$$

$$0 = \delta I_{ms}^2 + \delta I_{mt}^2 \tag{20}$$

since if $P$ is to be a maximum $\delta P$ must be zero for all possible variations.

From these 2 equations it is seen that

$$r_{ms} = r_{mt} \tag{21}$$

or that all the harmonic loads are equal for a maximum power. The filters are therefore unnecessary and a single star load absorbs the greatest power.

It may be shown that the power to such a star load depends only upon the resistances and the effective voltages and hence the assumption of given voltage wave forms was immaterial. Also given the effective voltages and line currents the star resistances are independent of the actual voltage wave forms.

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## Discussion

For discussion of this paper see page 779.

# Operating Aspects of Reactive Power

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***Synopsis.***—*This paper is written to present the point of view of the practical operating engineer to whom "reactive power" is something that he has to generate and deliver to his customers much as he does ordinary or real power. It happens that this kind of reactive power is the kind which causes the current to lag behind the voltage when it happens to be flowing in the same direction in the circuit as the "active" power. However, when it happens to be flowing in the direction opposite to that of the active power (which, in a transmission system is just about as likely to happen), it makes the total current in the circuit appear to lead the voltage and deceives the technician who observes this phenomenon into thinking that a different kind of reactive power (viz., leading reactive power) is flowing in the same direction as the active power.*

*The paper presents an interpretation of such observations in terms of the one kind of reactive power with which the practical operation and control of power systems has to deal and points out the parallelism between active and reactive power in their operating aspects.*

*It also presents an unorthodox metering technique for keeping track of the flow of reactive power in a complicated power transmission network which greatly clarifies and simplifies the problem of dispatching reactive power in such a system; such dispatching being necessary to obtain maximum transmission system capacity and efficiency as well as for system voltage control.*

*No pretense is made of presenting any newly discovered truths. Rather the attempt is to present a new way of looking at old truths. The point of view is believed to be somewhat novel and may do mild violence to some orthodox conventions. This violence, however, is believed to be justified by the resulting clarification in the operating aspects of reactive power.*

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THE subject of the symposium of which this paper is a part is "reactive power." This term is somewhat unfamiliar to many engineers, and some might even strongly deny the existence of reactive "power." The conception of reactive current as "wattless" is so deeply ingrained that the term "reactive power" will doubtless meet with reluctant acceptance. In one sense this conception of "wattlessness" is true, but in another, and the author believes, equally valid sense, it seems to him not to be true. The author therefore proposes to accept the title at its face value, and as an engineer in the operating field, present a point of view in which reactive power is conceived of as a kind of power different and distinct from power in its ordinary meaning (which hereinafter will be called "active" power) but with which the operator nevertheless has to deal in much the same manner.

### TWO VIEWS OF REACTIVE POWER

There are two points of view from which the subject of reactive power may be regarded. The first of these may be called the academic, mathematical, or technical point of view, and the second the practical, engineering, or operating point of view. Let us first clearly distinguish between these two points of view which we will call briefly the "academic" and the "practical."

### CHARACTERISTICS OF ACADEMIC VIEW

The academic point of view results from consideration of what is going on at a certain point in a circuit. Instruments are inserted and measurements made of current, potential, and power. From these it is often found that the measured watts are less than the product of the measured amperes and the measured volts by a certain factor, which we call the "power factor." From these relationships and familiar known laws, we can determine the in-phase and quadrature components of the flow (and their phase relationship) which in this view we think of as inseparable and more or less imaginary components of the "total kilovolt-amperes" in the circuit. While this technique does inform us fairly well as to what is occurring at the point of measurement, it does not lend itself at all well to the visualization of what is happening in the system as a whole nor to a practical technique of system control. It does not give us the picture of two independent things going on in the circuit at the same time.

In representing these quantities and relationships on paper the technician uses a device which he calls a "vector diagram." In such diagrams, counterclockwise vector rotation is usually considered standard, and right hand and upward vectors, positive. The "academic" viewpoint seems to have its origin in these conventions, as does also the question as to the "sign" of reactive power.

### CHARACTERISTICS OF PRACTICAL VIEW

The "practical" point of view results from a consideration of what is going on, not at one point in a circuit but throughout the entire electrical power system. The operating engineer is faced with the problem of controlling the operation of his system and hence is interested in tracing the two kinds of power flow found at any one point back, on the one hand, to their sources and forward, on the other hand, to their destinations, in order to discover how he can control their sources in and courses through the system. What does he find?

He finds that the active power (neglecting losses for the moment) originates in a prime mover, passes thence through a mechanical connection of some sort into a "generator" where it is converted into electrical power. After traversing the system this power arrives (let us say) at induction motors where it is converted back to mechanical power and passes on to the driven machines. Or it may be converted directly into heat and leave the electrical system in

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that form. In any case it flows, like a stream, into the electrical system at one end and out at the other.

He finds that the demand for reactive power originates for the most part in the excitation requirements of induction motors and other devices using iron magnetic circuits which draw their excitation, in the form of lagging reactive current, from the same circuits through which the active power is flowing. Following this reactive power back through the system he finds that it has its origin in the field circuits of the generators. He knows this must be so because he finds he can control the amount of reactive power supplied by any particular generator by varying its field current. This reactive power therefore apparently originates within the electromagnetic system and never leaves it, but reacts back and forth between the generators and the motors. Hence its name "reactive power" and its logical symbol *rkw* used hereinafter. [EDITOR'S NOTE: The author's symbol *rkw* (and the corresponding term *reactive kilowatt*) is used advisedly in this paper, rather than the standard editorial style *rkva*, or the symbol *kvar* adopted by the International Electrotechnical Commission, July 9, 1930.]

He further finds that the flow of the active power through his system produces comparatively little drop in potential, whereas the flow of reactive power is much more serious in this respect; also that if the reactive power is generated in the same generators through which active power is supplied, and flows through the same circuits, it requires increased current capacity of generators, transformers, and lines, increases $I^2R$ losses in all current carrying parts of the system, and limits the active power capacity of the transmission circuits. He finds, however, that active and reactive power do not add together in these circuits algebraically but geometrically in quadrature.

Since reactive power originates in generators and not in prime movers, the generation of reactive power is not subject to the same limitations as to geographical location as is that of active power, but can be generated anywhere desired. Therefore, in order to minimize its undesirable effects on the major parts of the system, reactive power generators (commonly called synchronous condensers) are frequently installed at receiving or distributing substations near the load where the reactive power is required. In many cases generators used to supply active power during one set of conditions may be used to supply reactive power during other conditions.

Since the active and reactive power do not add algebraically but combine in quadrature relation it is obviously more economical, other things being equal, to generate both in the same machine. Where both can be generated near the point of use, this usually proves to be the case, but where the active power must be transmitted long distances, it often proves more economical to generate the reactive power in separate machines near the load, even at the expense of increased total machine capacity. This practice also provides a means of regulating voltage at the receiving end of the lines.

As the two kinds of power—active and reactive—flow through the system, losses of both kinds occur due to the resistance, reactance, and capacitance of the circuits. The losses of active power, due to the resistance, are all positive with respect to the active power transmitted and result in less active power being received at the load than left the prime movers. The losses of reactive power, however, with respect to the reactive power transmitted, may be either positive or negative or both, positive losses being due to reactance and negative losses to condensance. It follows that the amount of reactive power delivered to the load may be either more or less than the amount generated.

Let us now inquire what are the conditions and problems confronting the power system operator in controlling his system. Briefly they are as follows:

1. A demand for active power by the customers of the system, and over which he has little or no control.
2. Sources of supply of active power in the form of steam and hydroelectric generating units, perhaps widely scattered, and over which he has control.
3. A demand for reactive power, principally for exciting the motors of the customers, and over which he has little or no control.
4. Various possible sources of reactive power including all of the synchronous generators, condensers, and motors on the system, and over most of which he has control.
5. The demands must be supplied from the various available sources in the most economical manner possible at all times.
6. Voltage must be maintained within certain limits at all stations on the system.

Various other conditions must usually be met but these are the ones with which reactive power is mostly concerned.

In order to operate his system efficiently, and properly control its voltage, the power system operator or load dispatcher must be able to control not only the sources, magnitudes, and directions of the active power flow but also the sources, magnitudes, and directions of the reactive power flow. The magnitude and direction of the active power flow are in practice controlled by adjusting the input to the proper prime movers. The magnitude and direction of the reactive power flow are similarly controlled by adjusting the field currents of the proper generators. To increase the amount of active power supplied by a prime mover the operator increases its power input by increasing its gate or throttle opening. Similarly, to increase the reactive power supplied by a generator or synchronous condenser operating in parallel with other synchronous machines, he increases its field excitation by adjusting its exciter or field rheostat. The two processes are analogous and parallel, but independent of each other.

## MEASURING INSTRUMENTS

The above are the processes by which the independent control of active and reactive power are effected. To know how to apply these controls, however, it is necessary to measure the magnitudes of the active and reactive power and for this purpose suitable instruments are necessary. The old technique of using wattmeters and power-factor meters was based upon the "academic" viewpoint, in which the total flow in the circuit was treated as a unit. The "practical" viewpoint calls for separate instruments to read the active power and the reactive power. Standard wattmeters will serve both purposes when suitably connected to the circuit. In circuits in which active power can flow in only one direction, left-hand zero instruments can be used for the active power. Where active power may flow in either direction, however, center zero instruments are commonly used. Since reactive power can flow in either direction in practically all circuits, center zero instruments are desirable to measure reactive power in practically all cases.

In the "academic" view, the sense or direction of the reactive power is defined by reference to that of the active power by saying that it "leads" or "lags" according as the current vector leads or lags the potential vector. In a circuit in which active power can flow in only one direction, such as a generator or a radial distribution circuit, this convention leads to little or no confusion. This, however, is not the case in a complicated power network, with widely distributed sources of active and reactive power, and with widely distributed loads, wherein almost any circuit may be called upon to transmit active and reactive power independently in either direction. In such a system, the sources and destinations of reactive power are visualized in the mind of the operator just as definitely as are the sources and destinations of the active power, and it consequently becomes much more natural and logical for him to relate the sense or direction of flow of the reactive power to the circuit in which it is flowing just as he does in the case of the active power rather than to relate it vectorially to the flow of the active power as in the conventional "academic" point of view. Thus, in this "practical" point of view the flows of active and of reactive power become entirely divorced from each other, the direction of flow of each being independently related to the circuit instead of one to the other.

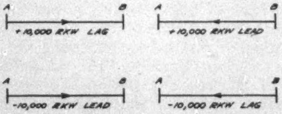
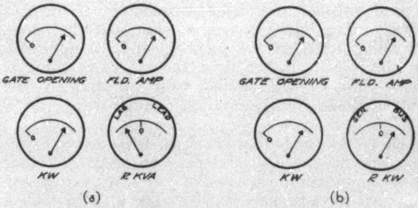


FIG. 1—FOUR WAYS OF DEFINING THE FLOW OF REACTIVE POWER IN A CIRCUIT

The conventional system of marking power factor and reactive power meters in terms of "lead" and "lag" thus, in a large power system, introduces difficulties in properly reading and interpreting the readings of these instruments. In a two-way circuit, owing to the reversible flow of active power, the interpretation of the readings is very confusing as it is impossible to tell, from the readings of the instruments marked in this way, the direction of the reactive power flow unless one knows how the instruments are connected.

Accepting the "practical" convention that reactive power flow is to be defined independently of the active power flow and in relation to the circuits in the same way as the active power flow is defined, it becomes necessary to adopt a convention as to the kind of reactive power that we will talk about. It immediately appears that with this method of treatment it is no longer necessary to discuss both leading and lagging reactive power, since leading reactive power flowing in one direction in the circuit is identical with lagging reactive power flowing in the other direction. Since, as above noted, in a normal electric power system the demand for lagging reactive power predominates over that for leading reactive power and furthermore since the demand for lagging reactive power has its origin in machines with the characteristics of which the operators are familiar and its source is in other machines with the characteristics of which the operators are also familiar, and over which they have control; whereas a demand for leading reactive power is of much rarer occurrence and less familiar to operating men, it follows that *the requirements of operation will be best served if all reactive power flow is treated as lagging reactive power flowing in a certain direction in the circuit.*



(a) (b)

FIG. 2—ACADEMIC (a) AND PRACTICAL (b) METHODS OF METERING THE OUTPUT OF A GENERATING UNIT

In the academic (conventional) method the field ammeter and reactive power meter pointers move in opposite directions when adjustments of field current are made. In the practical method this inconsistency is eliminated by reversing the connection of the "reactive kilowatt" meter

This is not difficult to do and when it is done consistently it results in the removal of a number of difficulties in handling reactive power flow on a power system. If, in the circuit *AB* of Fig. 1 there are 10,000 *rkw* lagging flowing from *A* to *B*, we can represent the same condition by saying there are −10,000 *rkw* lagging flowing from *B* to *A*, or there are 10,000 *rkw* leading flowing from *B* to *A*, or there are −10,000 *rkw* leading flowing from *A* to *B*. So, a leading *reactive kilowatt* in a circuit can always be represented by a lagging *reactive kilowatt* in the opposite direction; and vice versa, a lagging *reactive* *kilowatt* can always be represented by a leading *reactive kilowatt* in the opposite direction. Therefore, if we should decide to deal with only one kind of reactive power and further decide that that one kind shall be "lagging," any *reactive kilowatt* which formerly was called "leading" will now be called "lagging," with the direction of flow reversed. In Fig. 1 are shown the four different ways of representing exactly the same condition.

## CONVENTIONS FOR OPERATION

With the foregoing in mind, and with the aim to obtain a system which is simple and easy to understand and remember, the following conventions might be adopted by an operating power system.

1. Reactive power will always be represented in terms of lagging reactive power and will be designated by the symbol *rkw*.
2. On station log sheets and similar records all readings will be given as a flow between two points. The names of these two points will be written down in their proper order and connected by a dash or hyphen, such as: "Gen. No. 1–12-kv Bus" or "Lockport-Mortimer." (In this system, transmission circuits are designated by the names of the terminal bus points.) The magnitudes of the kilowatt and *reactive kilowatt* readings will then be recorded and an arrow written just before (or after) each quantity. These arrows will point in the direction of flow as referred to the corresponding points. For example, since "Lockport" is written to the left of "Mortimer" on the log sheet, if power flow is actually from Mortimer to Lockport, the arrow preceding the kilowatt figure will point to the left on the log sheet. Similarly, if reactive power flow is actually from Lockport to Mortimer, the arrow preceding the *reactive kilowatt* figure will point to the right on the log sheet.
3. In marking values of kilowatt and *reactive kilowatt* flow on diagrams, as a matter of convenience, only one arrow need be used to represent the direction of simultaneous flow of kilowatts and *reactive kilowatts* in the same circuit. This arrow may point in the actual direction of kilowatt flow. The kilowatt and *reactive kilowatt* quantities will then be marked beside the arrow. The kilowatt flow will be represented by a positive (+) quantity. The *reactive kilowatts* will be represented by a positive (+) quantity if its flow is actually in the same direction as the kilowatt flow, and by a negative (−) quantity if its flow is actually in the direction opposite to the kilowatt flow.

## APPLICATION OF THE CONVENTIONS—APPARATUS

If a generator, in parallel with other synchronous machines, is delivering active power only, an increase in field current will cause it to generate (lagging) reactive power, while a decrease in field current will cause it to consume (lagging) reactive power.

For the station operator, it may be interesting and helpful to note here that, having standardized on lagging reactive power, and adopted corresponding instrument connections and labelling (see Fig. 2) increasing the gate opening and increasing the field current of a generating unit operating in parallel with other synchronous machines have similar effects, in that the former causes an increase in kilowatt output (kilowatt meter pointer moves to the right) and the latter causes an increase in *reactive kilowatt* output (*reactive kilowatt* meter pointer moves to the right). Furthermore, it will be noted that the field ammeter pointer and *reactive kilowatt* meter pointer will always move in the same direction, that is, when one is moving from left to right, the other will also be moving from left to right, and vice versa. This consistency, uniformity, and simplicity are in striking contrast to the illogical and confusing inconsistency where the present "academic" standard marking and conventions are used, where lagging reactive output deflects the instrument pointer in the opposite direction from that of the field ammeter.

A synchronous condenser being a reactive power generator, a similar explanation applies. If the condenser is running at unity power factor (simply drawing kilowatts to supply internal losses), an increase in field current will cause it to deliver (lagging) reactive power to the circuit, while a decrease in field current will cause it to draw (lagging) reactive power from the circuit.

Unloaded transmission circuits have generally been said to be drawing leading reactive kilovolt-amperes but, according to the new conventions, we shall say they deliver (lagging) reactive power (*rkw*).

An induction motor draws (or consumes) (lagging) reactive power (*rkw*) from the circuit.

A static condenser delivers (lagging) reactive power (*rkw*) to the circuit.

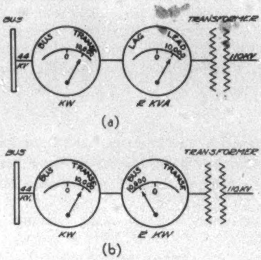


FIG. 3—ACADEMIC (a) AND PRACTICAL (b) METHODS OF METERING REVERSIBLE CIRCUITS

Interpretation of readings under academic method requires knowledge as to how reactive kilovolt-ampere meter is connected with reference to kilowatt meter, i. e., whether "lag" and "lead" apply to power flow from bus to transformer or from transformer to bus. With the practical method this knowledge is not needed, all the information required being provided by the labelling of the meter scales

## REACTIVE POWER (RKVA) (*RKW*) METER

In general practice, reactive kilovolt-amperes have been designated as being either "leading reactive kilovolt-amperes" or "lagging reactive kilovolt-amperes." Each of these, as above stated, can flow in either of two directions. On the other hand, active power (or simply power) has always been designated as just plain "kilowatts." In other words, in order to qualify a kilowatt meter reading completely, it has been necessary to state only magnitude and direction of flow, whereas, in the case of a reactive kilovolt-ampere meter reading, it has been necessary to state magnitude, kind (leading or lagging), and direction of flow.

Since, in this standardization, all reactive power will be represented in terms of lagging reactive power, both active power and reactive power values will be completely qualified by magnitude and direction of flow. "Reactive kilovolt-ampere" meters will now become "lagging *reactive kilowatt*" meters, and their readings will always be in lagging *reactive kilowatts*.

### *RKW* METER WITH TWO-WAY KW METER

In metering a piece of apparatus whose kilowatt flow is always in the same direction, no trouble should be experienced. Now, let us consider a piece of apparatus whose kilowatt flow may be in either direction. In Fig. 3 is a transformer connecting a 110-kv system with a 44-kv system. Assume the reactive kilovolt-ampere meter (conventional scale markings) is connected to indicate correctly for kilowatt flow from bus to transformer. Under the conventional method shown in Fig. 3(*a*) the meters indicate that 10,000 kw and 10,000 leading rkva are flowing from the 44-kv bus into the 44-kv side of the transformer. If the reactive kilovolt-ampere meter read "10,000" to the left of the zero point, the readings would be 10,000 kw and 10,000 lagging rkva flowing from the 44-kv bus into the 44-kv side of the transformer.

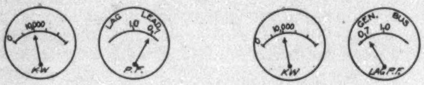


FIG. 4—ACADEMIC (a) AND PRACTICAL (b) USE OF TWO-QUADRANT POWER-FACTOR METERS

(a). 10,000 kw flowing from generator to bus. Leading reactive kilo-volt-amperes flowing from generator to bus. Ratio of kilowatts to total kilo-volt-amperes is 0.7

(b). 10,000 kw flowing from generator to bus. "Reactive kilowatts" flowing from bus to generator. Ratio of kilowatts to kilovolt-amperes is 0.7

In accordance with convention No. 1, previously stated, the markings on the reactive kilovolt-ampere meter will be changed to those shown in Fig. 3(*b*) the reactive kilovolt-ampere meter connections being reversed to produce this result. As before, the kilowatt meter indicates 10,000-kw flowing from bus to transformer. The *reactive kilowatt* meter indicates 10,000 *rkw* flowing from transformer to bus.

It should be noted that, in Fig. 3(*a*) correct reactive kilovolt-ampere meter readings can be obtained only when the reader knows how the reactive kilovolt-ampere meter is connected, i. e., for which direction of kilowatt flow the reactive kilovolt-ampere meter markings "lead" and "lag" apply. On the other hand, with the new *reactive kilowatt* meter markings shown in Fig. 3(*b*) the reader never has to worry about instrument connections.

### POWER-FACTOR METERS

Power-factor meters where already installed may be treated the same as *reactive kilowatt* meters, as is shown in the following paragraph.

A power-factor meter really indicates direction of *reactive kilowatt* flow. In this standardization, the instrument will *always* be a "lagging power-factor meter." In other words, it will always be used to indicate the direction of flow of (lagging) reactive power. At the same time, of course, its scale is so calibrated as to give the ratio of kilowatt to kilovolt-amperes, regardless of the relative directions of kilowatt and *reactive kilowatt* flow. In Figs. 4 and 5 are illustrations. To obtain consistent meter labelling requires reversal of the conventional connections of the power-factor meter in each case.

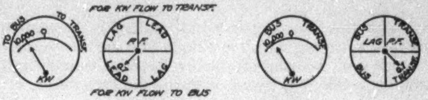


FIG. 5—ACADEMIC (a) AND PRACTICAL (b) USE OF FOUR-QUADRANT POWER-FACTOR METERS

(a). 10,000 kw from transformer to bus. Leading reactive kilovolt-amperes from transformer to bus. Ratio of kilowatts to total kilovolt-amperes is 0.7

(b). 10,000 kw from transformer to bus. "Reactive kilowatts" from bus to transformer. Ratio of kilowatts to kilovolt-amperes is 0.7

### LOG SHEETS AND DIAGRAMS

To illustrate the application of the conventions to log sheets, let us see how the readings of Fig. 3(*b*) would be recorded. The readings are 10,000 kw flowing from 44-kv bus to transformer and 10,000 *rkw* flowing from transformer to 44-kv bus. These readings would appear on the station log sheet as follows:

| Circuit | Kw | *Rkw* |
|---|---|---|
| 44-Kv Bus—Transformer No. 2 | → 10,000 | ← 10,000 |

The instrument readings pictured in Fig. 5 would be entered in a log sheet as follows:

| Circuit | Kw | Lag P.F. |
|---|---|---|
| Bus—Transformer No. 12 | ← 10,000 | → 0.7 |

If the log entry for the condition pictured in Fig. 3(*b*) was to be transferred to a system diagram it would be written as shown in Fig. 6. In this method, having standardized on lagging *reactive kilowatts*, in diagrams lagging *reactive kilowatts* will be positive and leading *reactive kilowatts* (if ever referred to) will be negative.

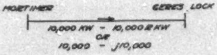


FIG. 6—APPLICATION OF PRACTICAL REACTIVE POWER TECHNIQUE TO DIAGRAMS

### VOLTAGE CONTROL

In a compact electrical system it is frequently possible to obtain satisfactory voltage control at substation busses by regulation of generator voltage. Generator voltage control will not, however, provide proper substation voltage regulation in an electrical system with long transmission lines. Additional facilities must be provided at some of the receiving substations to allow proper voltage control at these points. This voltage control is best provided in many cases by reactive power generators (synchronous condensers) at the receiving substations. In this application reactive power generators may be thought of as having two functions. One is the supply of the reactive power to the local load. This relieves the transmission system and power generators of the burden of the reactive power. The other function is that of sending reactive power back over the transmission circuits in the opposite direction for the purpose of voltage control. By this means a voltage gradient in one direction due to flow of active power may be compensated for by a gradient in the opposite direction due to flow of reactive power, thus making possible the maintenance of practically a flat voltage level over the whole system.

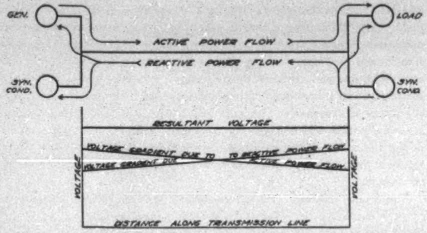

GEN.
LOAD
ACTIVE POWER FLOW
REACTIVE POWER FLOW
SYN. COND.
SYN. COND.
RESULTANT VOLTAGE
VOLTAGE GRADIENT DUE TO TO REACTIVE POWER FLOW
VOLTAGE GRADIENT DUE ACTIVE POWER FLOW
VOLTAGE
VOLTAGE
DISTANCE ALONG TRANSMISSION LINE

FIG. 7—APPLICATION OF PRACTICAL REACTIVE POWER TECHNIQUE TO SYSTEM VOLTAGE CONTROL

**Voltage gradients due to flow of active and reactive power compensate for each other producing practically flat voltage level**

### CONSUMER METERING

In consumer metering we are concerned only with what is taking place at a certain point in the circuit, namely, the point of delivery to the customer, and not at all with the questions of sources and control. For this purpose therefore the "academic" approach and technique are applicable. Present practices in metering customers which take large amounts of reactive power in proportion to their consumption of active power, may in some cases leave something to be desired, but it is doubtful if independent metering of the active and reactive components of the customer's load would be justified in many cases, since present rates doubtless are adjusted to an average situation from which only a few instances would widely depart. An inexpensive means of measuring kilovolt-amperes directly or measuring the arithmetic difference between the kilovolt-amperes and the kilowatts may ultimately prove useful in this field.

### CONCLUSION

The "practical" conception of reactive power as herein outlined, in which the generation, metering, and control of active and reactive power are consciously divorced from each other, results in a simplified technique of power system operation which greatly facilitates the control of the system and the maintenance of maximum system efficiency.

## Discussion

For discussion of this paper see page 779.

# Power, Reactive Volt-Amperes, Power Factor

BY C. L. FORTESCUE*

Fellow A.I.E.E.

***Synopsis.***—*The relation between power, reactive volt-amperes, and power factor is discussed for sinusoidal electromotive forces and currents. Reactive volt-amperes is defined as the flow of stored energy into the circuit and is deduced from the stored energy cycle. It is shown to be a cyclic flow of power which is 90 deg in advance of the cyclic part of the dissipation or power input cycle which with the stored energy cycles is positive at all instants. This leads to the vector equation* $\breve{E}\mathring{I} + \bar{E}\breve{I}$ *derived for the equation of total inflow of energy given by* $Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right)$ *or* $\left(Ri^2 + L\frac{di}{dt}i\right)$ *for an inductive system or* $Ri_2 + \frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right)$ *or* $\left(Ri + \frac{q}{C}\right)i$ *for a capacitor system.*

*Non-sinusoidal electromotive forces and currents are discussed and it is shown that there is no simple relation between the volt-amperes as obtained by voltmeters and ammeters and power as obtained by wattmeters and reactive power. The inflow of stored energy for double frequency fundamental can be obtained but it appears to bear little relation to the product of mean square volts and amperes and true average power. It is concluded that the ratio of power to mean square volt-amperes is a useful practical factor with non-sinusoidal waves encountered in practice but should not be used to define reactive volt-amperes.*

*Polyphase power and reactive volt-amperes are defined. In a balanced system power is continuous and the instantaneous reactive volt-amperes are zero. Nevertheless, a polyphase balanced system has a power factor which is the same as that of each phase. In an unbalanced system each symmetrical component has a power factor and in addition there is interchange of power between phases resulting from unbalance so that each phase has an individual power factor. It is shown that the positive phase sequence power and reactive volt-amperes, if the generator supplying power is symmetrical, include both the negative and positive phase sequence power and reactive volt-amperes; that is, the source of all power and stored energy is the positive sequence, and the positive phase sequence flow of energy gives the correct measure of the power factor of the system.*

*Non-linear circuits are characterized by frequency conversion. If such are supplied from a sinusoidal generator, all the harmonic power and reactive volt-amperes must be supplied from the fundamental frequency which is the source of the whole power and reactive volt-ampere output. Therefore, the fundamental frequency power and reactive volt-amperes properly define the true power factor of the system.*

## INTRODUCTION

THE current ideas regarding the relations between power, reactive volt-amperes, volt-amperes, and power factor were the outcome of an attempt to express the theory of electric circuits subjected to non-sinusoidal electromotive forces in terms of an equivalent sine wave. The equivalent sine wave of a non-sinusoidal wave is a sine wave having the same mean square value as the non-sinusoidal wave. In the elementary theory of electric circuits it was assumed that non-sinusoidal electromotive forces impressed on a linear electric system could be replaced by their equivalent sine waves without causing substantial error in the result, which implied that the wave form of the currents set up in the system was the same as that of the impressed electromotive forces. Later on engineers came to realize that this specification for non-sinusoidal waves was inadequate and another factor was introduced, namely, form factor which was defined as the ratio of maximum value of the actual wave to that of the equivalent sine wave. This factor did not help to any extent in defining the relations between volt-amperes, reactive volt-amperes, and power for non-sinusoidal waves, for the simple reason that these quantities are not definable by means of two factors.

## ELEMENTARY THEORY OF ENERGY FLOW RELATIONS IN LINEAR ELECTRIC CIRCUITS

A linear circuit, however complex, is defined as one in which an applied sinusoidal electromotive force will produce only sinusoidal currents. The characteristic of such a system or net is defined by the principle of superposition which for the present purpose may be stated as follows: If the connections of a linear net *remain unchanged* during the introduction of any electromotive forces in the net either simultaneously or in any sequence whatever, the resulting currents are the same as if each electromotive force were applied to the network at rest individually at the proper instant and the resulting currents superposed. Thus each electromotive force acts upon the system as if it were independent of all the others. The fact that the system must remain unchanged during the introduction of these electromotive forces has been emphasized for the reason that it is not always realized that the closing of a pair of terminals through a generator changes a network and, therefore, the principle of superposition no longer holds. In the case we are considering, however, it is supposed that certain electromotive forces are already established and they may be considered as having been introduced simultaneously or separately without any change in the network. Commercial systems are never strictly linear, on account of the presence of iron in the circuits of electric machines, but the effect of such non-linear elements in the system in general may be ignored. There are cases, however, where they become of importance, such as, for example, cases of telephone interference. In such cases each harmonic must be considered independently with reference to its source.

If we consider a linear system in which all the elements consist of resistance and self-inductance with a sinusoidal electromotive force impressed, the relations between volt-amperes, power, and reactive volt-amperes are expressed as follows where $E$ and $I$

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are the root mean square values of electromotive force and current

$$\left.\begin{aligned} \text{Electromotive force} &= E\cos\omega t \\ \text{Current} &= I\cos(\omega t-\alpha) \\ \text{Volt-amperes} &= EI \\ \text{Power} &= EI\cos\alpha \\ \text{Reactive Volt-amperes} &= EI\sin\alpha \end{aligned}\right\} \quad (1)$$

We may represent the electromotive force $E\cos\omega t$ by two equal vectors of length equal to one-half the mean square value, one rotating positively the other negatively, denoting the positively rotating vector $\check{E}$ and the negatively rotating vector by $\hat{E}$

$$\begin{aligned} e &= \sqrt{2}\,E\cos\omega t = \frac{\check{E}+\hat{E}}{\sqrt{2}} = \frac{Ee^{j\omega t}+Ee^{-j\omega t}}{\sqrt{2}} \\ i &= \sqrt{2}\,I\cos(\omega t-\alpha) = \frac{\check{I}+\hat{I}}{\sqrt{2}} = \frac{Ie^{(j\omega t-\alpha)}+Ie^{-(j\omega t-\alpha)}}{\sqrt{2}} \qquad (2) \\ ei &= \frac{\check{E}\hat{I}+\hat{E}\check{I}}{2}+\frac{\check{E}\check{I}+\hat{E}\hat{I}}{2} \end{aligned}$$

In the vector representation of electromotive forces and currents the convention is to use the positively rotating vectors $E$ and $I$. It will be observed that $\check{E}$ and $\check{I}$ enter into the expression for $ei$ symmetrically and therefore with equal authority. On the other hand in practical problems $\check{E}$ is the known function of the independent variable $t$ while $\check{I}$ is the dependent function, it would therefore seem consistent to define energy flow into the circuit by

$$P + jQ = \check{E}\hat{I} \qquad (3)$$

This convention is seen also to be consistent with the d-c analogy; namely, since the impedance $Z$ in an a-c system takes the place of resistance $R$ in a d-c system then

$$\left.\begin{aligned} &\text{Direct current} \begin{cases} E = RI \\ \text{Power} = EI = RI^2 \end{cases} \\ &\text{Alternating current} \begin{cases} \check{E} = Z\check{I} \\ P + jQ = \check{E}\hat{I} = ZI^2 \end{cases} \end{aligned}\right\} \quad (3)$$

The above arguments, logical as they appear to the writer, may not be convincing to some. For such it will be necessary to deduce the equation of flow of energy into a circuit from the equation of energy. In a circuit having resistance and inductance in series the rate of dissipation of energy or power is

Dissipation $= Ri^2$
The kinetic energy is

$$T = \frac{1}{2}Li^2$$

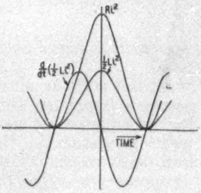
Therefore, the flow of energy is

$$Ri^2 + \frac{d}{dt}\left(\frac{1}{2}Li^2\right) \quad \text{or} \qquad (4)$$

$$\left(Ri + L\frac{di}{dt}\right)i \qquad (5)$$

Now a little consideration will convince any one familiar with dynamical systems that the instant at which the kinetic energy reaches a maximum must coincide with the instant of maximum dissipation of energy through friction, and the epoch of maximum rate of storage must necessarily take place prior to that of maximum storage and therefore prior to that of maximum rate of dissipation. In a non-conservative system constrained to move under a sinusoidal force the cycle of stored energy in the system coincides in phase with the cycle of energy rate of dissipation; the total kinetic energy is always positive. The rate at which energy is stored into the system or the work done by the force in producing motion against the inertia of the system is $\frac{d}{dt}\left(\frac{1}{2}Li^2\right)$. The maximum inflow of stored energy therefore occurs when the stored energy is one-half its maximum and increasing, and therefore when the rate of dissipation is one-half its maximum value and increasing, and the maximum outflow of stored energy occurs at the same point of the stored energy cycle when it is decreasing, that is at the same point of the decreasing dissipation cycle. The cycle of inflow of stored energy is therefore in *phase advance* of the cycle of dissipation or power inflow by a right angle.

These cyclic flow of energy relations are shown in Fig. 1, as expressed by eq 4 and in Fig. 3 for those who are happier when dealing with electromotive forces and currents these relations are shown as expressed by eq 5.



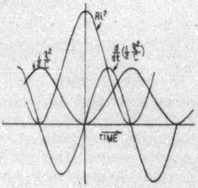


FIG. 1 (LEFT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 4 FOR RESISTANCE AND INDUCTANCE IN SERIES

FIG. 2 (RIGHT)—FLOW OF ENERGY RELATIONS AS EXPRESSED BY EQ 6 FOR RESISTANCE AND CAPACITY IN SERIES

For a circuit having potential energy, the stored energy is

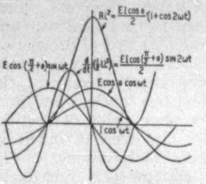
$$W = \frac{1}{2}\frac{q^2}{C}$$

where $q$ is the change at any instant and $C$ is the capacity. The inflow of energy into the system is given by

$$Ri^2 + \frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right) \quad \text{or} \qquad (6)$$

$$\left(Ri^2 + \frac{q}{C}\right)i \qquad (7)$$

In the dynamical analogy $q$ is the coördinate of the motion, $i$ is the velocity. Starting with maximum velocity at time zero, the spring (supposed to be linear) will have reached $^1/_2$ its maximum deflection and the maximum stored energy will occur when the velocity becomes zero, that is, when $Ri^2$ is zero. Thus the cycle of energy storage is of exactly the same form as that of the rate of dissipation of energy but lagging 180 deg. Therefore, the cycle of inflow of potential energy $\frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right)$ will lead the energy storage cycle by 90 deg and will lag the rate of energy dissipation cycle by 90 deg. In Fig. 2 is shown this expressed in terms of the dissipation and stored energy cycle as given by eq 6, and in Fig. 4 in terms of current and electromotive forces as in eq 7.



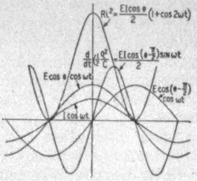
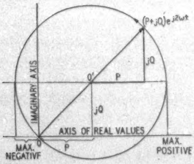


Fig. 3 (Left)—Flow of Energy Relations as Expressed by Eq 5 for Resistance and Inductance in Series

Fig. 4 (Right)—Flow of Energy Relations as Expressed by Eq 7 for Resistance and Capacity in Series

In dealing with cyclic quantities such as alternating currents and electromotive forces the convention has been standardized of representing such quantities by positively rotating vectors in the complex plane, the projection of these vectors on the real axis giving the instantaneous value or, where $\check{E}$ and $\hat{I}$ are root mean square, the instantaneous values divided by $\sqrt{2}$. The only difference between energy flow values and currents and electromotive forces is that the axis of rotation of the former is displaced from the origin by the amount $P + jQ = \check{E}\hat{I}$ which gives the mean power or rate of dissipation as the abscissa and the value of the rate of energy storage which is a purely sinusoidal quantity as ordinate. The rotating vector is the quantity $\check{E}\hat{I}\ e^{j2\omega t}$ rotating about the displaced axis of rotation which since at $t = 0$, $\check{I}$ and $\hat{I}$ are both wholly real gives $\check{E}\hat{I}\ e^{j2\omega t} = \check{E}\hat{I}$.



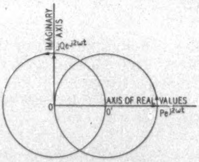


Fig. 5 (Left)—Vector Diagram of Instantaneous Energy Flow as Expressed by Eq 8 for Resistance and Inductance in Series

Fig. 6 (Right)—Vector Diagram of Component Power and Reactive Volt-Amperes as Expressed by Eq 9 for Resistance and Inductance in Series

The instantaneous power vector diagram therefore is properly expressed by

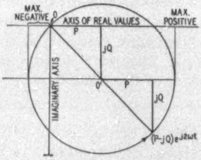
$$ei = \left.\begin{array}{l}\text{real part of } \check{E}\hat{I} + \check{E}\hat{I}, \text{ or}\\ \check{E}\hat{I}(1 + e^{j2\omega t}), \text{ or}\\ (P + jQ)(1 + e^{j2\omega t})\end{array}\right\} \quad (8)$$

If it is desired to obtain the diagram in terms of the cyclic components of $P$ and $jQ$ we should leave $jQ$ out in the last equation, since it is stationary and its projection on the real axis is zero. This gives the expression:

$$ei = P(1 + e^{j2\omega t}) + jQe^{2\omega t} \quad (9)$$

where $P$ is the real part of $\check{E}\hat{I}$ and $jQ$ its imaginary part.

These two diagrams are given in Figs. 5 and 6. The diagram of Fig. 5, following eq 8, may be called the *instantaneous energy flow vector diagram,* while Fig. 6, following eq 9, may be called the *component power and reactive volt-ampere vector diagram.* The sum of the projections of Fig. 6 on the real axis corresponds in value and time with the projections of Fig. 5 on the real axis. These diagrams are based on circuits having kinetic energy in operation. Similar diagrams for circuits having potential energy are shown in Figs. 7 and 8, and the same eqs 8 and 9 apply, $Q$ in this case being negative.



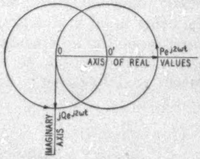


Fig. 7 (Left)—Vector Diagram of Instantaneous Energy Flow as Expressed by Eq 8 for Resistance and Capacity in Series

Fig. 8 (Right)—Vector Diagram of Component Power and Reactive Volt-Amperes as Expressed by Eq 9 for Resistance and Capacity in Series

In eq 4 if we take $i = I\cos\omega t$, where $I$ is the maximum instantaneous value of $i$,

$$\begin{aligned} Ri^2 &= RI^2\cos^2\omega t\\ &= \frac{RI^2}{2} + \frac{RI^2}{2}\cos 2\omega t\\ {}^1/_2\,Li^2 &= \frac{1}{2}LI^2\cos^2\omega t\\ \frac{d}{dt}\left(\frac{1}{2}Li^2\right) &= -\omega LI^2\cos\omega t\sin\omega t\\ &= -\frac{1}{2}LI^2\sin 2\omega t\\ &= \frac{1}{2}LI^2\cos\left(2\omega t + \frac{\pi}{2}\right)\end{aligned}$$

Flow of energy

$$= \frac{RI^2}{2} + \left\{\frac{RI^2}{2}\cos 2\omega t + \omega\frac{LI^2}{2}\cos\left(2\omega t + \frac{\pi}{2}\right)\right\} \quad (10)$$

$$= \frac{RI^2}{2} + \left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right)e^{j2\omega t} +$$

$$\left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right)e^{-j2\omega t}$$

$$= \left\{\left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right) + \left(\frac{RI^2}{4} + j\omega\frac{LI^2}{4}\right)e^{j2\omega t}\right\} +$$
$$\left\{\left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right) + \left(\frac{RI^2}{4} - j\omega\frac{LI^2}{4}\right)e^{-j2\omega t}\right\}$$

Choosing positive rotation for vector representation of power we have

$$\begin{aligned}\text{Flow of energy} &= \frac{RI^2}{2} + j\omega\frac{LI^2}{2} + \left(\frac{RI^2}{2} + j\omega\frac{LI^2}{2}\right)e^{j2\omega t}\\ &= \check{E}\hat{I} + \check{E}\hat{I}e^{j2\omega t} \qquad (11)\\ &= \check{E}\hat{I} + \check{E}\check{I}\end{aligned}$$

Eqs 9 and 10, and the component circle diagram Fig. 6 correspond. Eqs 8 and 11 are those for Fig. 7 which is a single circle diagram giving the instantaneous power or flow of energy.

## SINGLE PHASE NON-SINUSOIDAL ELECTROMOTIVE FORCES AND CURRENTS

In the solution of linear circuits with non-sinusoidal electromotive forces applied it was shown that each harmonic of electromotive force is considered independent of the fundamental electromotive force and the other harmonics. Each harmonic therefore has its own power input, stored energy cycle, reactive volt-amperes, and power factor as if the others did not exist. If we consider the harmonic reactive volt-amperes with respect to the fundamental reactive volt-amperes, it is seen that the integral of the even harmonics over one-half cycle of the fundamental reactive volt-amperes is always zero, and for the odd harmonics will vary from zero up to the integral of one-half a harmonic reactive cycle. The amount added to the reactive volt-amperes during $^1/_2$ cycle of fundamental reactive volt-amperes for each harmonic is zero for all even and zero to $\pm\frac{1}{\pi}$ the integral over $^1/_2$ cycle of the odd harmonic, depending upon the phase position with respect to the fundamental reactive volt-ampere cycle. The contribution to the fundamental reactive volt-ampere cycle of the harmonic therefore is indeterminate from the root mean square volts and amperes showing that there is no such thing as the equivalent sine wave for non-sinusoidal currents and electromotive forces.

If the wave form of applied electromotive force is known the stored energy cycle for the fundamental component current and its harmonics are completely defined, and therefore the respective power inputs, reactive volt-amperes, and instantaneous powers are known for each harmonic and the whole instantaneous power cycle and fundamental reactive volt-ampere cycle can be obtained by composition of their individual values as pointed out, but the values obtained in this way cannot be derived from the mere measurement of the root mean square volts and amperes of the circuit.

In practical circuits the distortion is usually negligible and therefore power factor as defined should be retained as a convenient practical measure of the ratio of mean volt-ampere to mean power input or mean rate of dissipation. For analytical work where harmonics are large in comparison with the fundamental, equivalent sine waves should never be used, but each harmonic should be considered independently.

## POWER AND REACTIVE VOLT-AMPERES IN A SINGLE-PHASE LINEAR NETWORK

The method of obtaining power and reactive volt-amperes for a linear single-phase network may be generalized by using the Lagrangian energy function and Rayleigh dissipation function. If $i_1$, $i_r$, $i_n$ are the instantaneous currents flowing into $n$ terminals of the network and if it is supposed that the Lagrangian function $T-W$ (where $T$ is kinetic energy and $W$ is potential energy) and the dissipation function $F$ have been expressed in terms of the terminal currents, then

$$\text{Instantaneous power input at } r^{th} \text{ terminal} = i_r\frac{\delta F}{\delta i_r}$$

$$\text{Instantaneous inflow of stored energy} = \left(\frac{d}{dt}\frac{\delta(T-W)}{\delta i_r} - \frac{\delta(T-W)}{\delta q_r}\right)i_r$$

$$\text{Instantaneous power input} = \left\{\frac{\delta F}{\delta i_r} + \frac{d}{d_t}\frac{\delta(T-W)}{\delta i_r} - \frac{\delta(T-W)}{\delta q_r}\right\}i_r$$

This expression is quite general and applies for both sinusoidal and non-sinusoidal currents, and when the terminals supply induction motors and synchronous motors as well as simple impedances. For sinusoidal waves it gives the same result as the vector expression

$$P_r + jQ_r = \check{E}_r\hat{I}_r + \check{E}_r\check{I}_r$$

which has been shown to be the vector representation of instantaneous power.*

## POWER, REACTIVE VOLT-AMPERES, AND POWER FACTOR OF POLYPHASE CIRCUITS

It is not necessary to consider the general polyphase system. It is sufficient for practical purposes to deal with the three-phase system. Here as shown in "Polyphase Power Measurements" by C. L. Fortescue, A.I.E.E. TRANS., v. 42, 1923, p. 358–71, the system if sinusoidal can be completely characterized by the use of the sequence symbols $S^0$, $S^1$, $S^2$, and the conjugate symbols $S^0$, $S^{-1}$, $S^{-2}$, the zero sequence system being self conjugate. Thus the currents are given in all phases by

$$S^0\check{I}_{A0} + S^1\check{I}_{A1} + S^2\check{I}_{A2}$$

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*In ordinary linear networks the total inflow of stored energy can be expressed simply as follows:

$$\text{Total instantaneous inflow of stored energy} = \frac{dT}{dt} + \frac{dW}{dt}.$$

The portion of this to be assigned to the $r$th terminal is that part of $\frac{dT}{dt}$ containing $i_r$ and that part of $\frac{dW}{dt}$ containing $q_r$. For the instantaneous power input at the $r$th terminal the quantity $\frac{\delta F}{\delta i_r}$ must be added.

$A$ being the principal phase, and the electromotive force

$$S^0\breve{E}_{A0} + S^1\breve{E}_{A1} + S^2\breve{E}_{A2}$$

Power as in single-phase circuits is defined by $\breve{E}\hat{I}$ so that total power is

$$\Sigma(S^0\breve{E}_{A0} + S^1\breve{E}_{A1} + S^2\breve{E}_{A2})\quad(S^0\hat{I}_{A0} + S^{-1}\hat{I}_{A1} + S^{-2}\hat{I}_{A2})$$

which gives

$$\begin{aligned}&3(\breve{E}_{A0}\hat{I}_{A0} + \breve{E}_{A1}\hat{I}_{A1} + \breve{E}_{A2}\hat{I}_{A2}) +\\ &\Sigma(S^{-1}\breve{E}_{A0}\hat{I}_{A1} + S^{-2}\breve{E}_{A0}\hat{I}_{A2} + S^1\breve{E}_{A1}\hat{I}_{A0} + S^2\breve{E}_{A2}\hat{I}_{A0}) +\\ &\Sigma(S^{-1}\breve{E}_{A1}\hat{I}_{A2} + S^1\breve{E}_{A2}\hat{I}_{A1})\end{aligned}$$

The instantaneous sum of the expressions having $S^{-1}$, $S^{-2}$, $S^1$, and $S^2$ preceding them is zero. They are the quantities which define the interchange of power and reactive volt-amperes among phases. This is characteristic of unbalanced polyphase systems and unbalance factors are associated with those interchanges.

If we take the product

$$(S^0\breve{E}_{A0} + S^1\breve{E}_{A1} + S^2\breve{E}_{A2})\quad(S^0\check{I}_{A0} + S^1\check{I}_{A1} + S^2\check{I}_{A2})$$

we obtain

$$\begin{aligned}&\Sigma S^2\breve{E}_{A1}\check{I}_{A1} + S^1\breve{E}_{A2}\check{I}_{A2}\\ &\Sigma S^1\breve{E}_{A0}\check{I}_{A1} + S^2\breve{E}_{A0}\check{I}_{A2} +\\ &\quad 3\breve{E}_{A0}\check{I}_{A0} + 3(\breve{E}_{A1}\check{I}_{A2} + \breve{E}_{A2}\check{I}_{A1})\end{aligned}$$

It will be observed that the first term is the total inflow of reactive volt-amperes for each balanced system comprising the symmetrical coördinates, except the zero sequence term, and these are zero since they are preceding by $S^1$ and $S^2$ showing that the total flow of energy is uniform in a balance system. The terms $3\breve{E}_{A0}\check{I}_{A0} + 3(\breve{E}_{A1}\check{I}_{A2} + \breve{E}_{A2}\check{I}_{A2})$ are connected with the interchange of power and reactive power between phases and it is seen that these double frequency products are not zero. The flow of power in an unbalanced polyphase system is not uniform. The equation gives the average power factor of each symmetrical component of an unbalanced system and of course if the system is balanced, zero and negative sequence are not present and the expression $\Sigma S^0\breve{E}_{A1}\hat{I}_{A1} = 3\breve{E}_{A1}\hat{I}_{A1}$ gives not only the mean power but also the reactive volt-amperes which divided by three is the reactive volt-amperes per phase. Space does not permit of going exhaustively into the subject of polyphase power and reactive volt-ampere measurements but the following important points should be noted.

1. In a balanced system the total instantaneous reactance volt-amperes is zero. The volt-amperes per phase are given by the imaginary part of the product $3\breve{E}_{A1}\hat{I}_{A1}$.

2. In an unbalanced system there are three such products representing power and reactive volt-amperes of each symmetrical component.

3. In an unbalanced system supplied from a symmetrical generator the total power and reactive volt-amperes including that of the negative and zero sequence components are included in the positive sequence components so that the expressions $3\breve{E}_{A1}\hat{I}_{A1}$ gives the true measure of power and reactive volt-amperes that is supplied by the generators. The individual power factor per phase of each generator must be obtained by computing the total current and total electromotive force for each phase in the regular way.

## NON-LINEAR CIRCUITS

The analysis of non-linear circuits is complicated mathematically so only a brief sketch of the main characteristics will be given. The fundamental characteristic of such circuits is that sinusoidal power taken in is partly absorbed as such and partly converted into harmonic power which is either dissipated in the system or made use of. Examples of non-linear circuits are:

1. Magnetizing circuit of transformers and other electrical apparatus using iron.
2. Mercury arc and thermionic rectifier.
3. Power arcs.

If all the power for such networks is supplied from a sinusoidal source, the total power and reactive volt-amperes delivered will be given by the power and reactive volt-ampere input of the fundamental sinusoidal impressed electromotive force.

## CONCLUSIONS

Following are conclusions which may be drawn:

1. For a sine wave the dissipation cycle and the stored energy cycle are fundamental concepts and are easily obtained. The power input is given by the dissipation cycle and the inflow of stored energy by the differential with respect to time of the stored energy cycle. The sum of these three cycles gives the instantaneous power cycle. The vector expression for this is $\breve{E}\hat{I} + \breve{E}\check{I}$ the second term being double frequency. $\breve{E}\hat{I}$ being equal to $P + jQ$ gives the proper point on the complex plane for the center of rotation of the positively rotating vector $\breve{E}\check{I}$.

2. In 3 phase sinusoidal balanced systems the total power input from a generator is continuous. The total reactive volt-amperes is zero but per phase it is given by $\breve{E}_{A1}\hat{I}_{A1} + \breve{E}_{A1}\check{I}_{A1}$ vectorially. When there is unbalance the polyphase power input at an unbalanced terminal is given by $3(\breve{E}_{A1}\hat{I}_{A1} + \breve{E}_{A2}\hat{I}_{A2} + \breve{E}_{A0}\hat{I}_{A0})$. If the source of power is a symmetrical machine the total power and reactive volt-amperes input including the power and reactive volt-amperes circulated in the system by the zero and negative sequence components are given by $3\breve{E}_{A1}\hat{I}_{A1}$, and this gives the true power and reactive volt-amperes input to the system.

3. Non-linear circuits are characterized by frequency changing so that fundamental power and reactive volt-amperes are taken in and converted into power and reactive volt-amperes at higher or lower frequencies. Here again in general the power and reactive volt-amperes measured at fundamental frequency define the true power and reactive volt-amperes supplied by the sine wave generator.

## Discussion

For discussion of this paper see page 779.

# Reactive Power and Power Factor

BY W. V. LYON[1]

Fellow, A.I.E.E.

It is the purpose of this paper to discuss the terms, reactive power and power factor; to see if they may be defined by some general mathematical principles so that when so defined they will be useful in the calculation of electric circuits; and to see what limits there are, if any, to a physical interpretation of these mathematical definitions.

The value of a steady alternating electromotive force, $e$, or current, $i$, is mathematically defined as its root mean square value:

$$E_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2\,dt} \text{ volts}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2\,dt} \text{ amperes}$$

where $T$ is the time of one cycle, *i.e.*, the reciprocal of the frequency.

The mathematical definition of the power, $P$, supplied to a circuit, where the potential across the circuit and the current through it are $e$ and $i$ is:

$$P = \sqrt{\frac{1}{T}\int_0^T ei\,dt} \text{ watts}$$

The advantages of these definitions of electromotive force, current and power have long been recognized by international agreement. Recently it has likewise been agreed that reactive power shall be defined mathematically by the expression $EI \sin \theta$; where $E$ is the root mean square magnitude of the sinusoidal potential (volts) across the circuit, $I$ is the root mean square magnitude of the sinusoidal current (amperes) in the circuit, and $\theta$ is their relative phase. It was further agreed that the unit of reactive power shall be the "var." The total reactive power supplied to a network is the algebraic sum of the reactive powers supplied to its branches. It is thus highly desirable that an agreement should be reached in regard to the sign of the angle $\theta$; that is, whether $\theta$ is to be taken as positive for condensive or for inductive loads. In other words, whether the reactive power is to be positive for a condensive or for an inductive load. In this paper the author has assumed that the angle $\theta$ is *positive* when the current *leads* the potential across the circuit, and *negative* when it *lags*. Some have adopted the opposite convention.

The limitation of a sinusoidal time variation for the potential and current in the present definition of reactive power is unnecessary. The reactive power may be more broadly defined as $\Sigma E_h I_h \sin \theta_h$; where $h$ represents the order of the individual harmonics in the potential and current. That is, the total reactive power for any circuit may be defined as the sum of the reactive powers in the circuit due to the different harmonic components of potential and current. This latter definition of reactive power is not limited by the wave form of the applied electromotive force or by the constancy of the circuit "constants" or, in polyphase cases, by the number of the phases or their symmetry. It is as broad as and corresponds to the accepted definition of (active) power which in the case of non-sinusoidal potentials and currents can be expressed as $\Sigma E_h I_h \cos \theta_h$. Hereafter this definition of reactive power, $\Sigma E_h I_h \sin \theta_h$, will be referred to as the "mathematical definition."

In what follows, except as noted, the letters $E$, $I$, and $S$ are vector quantities whose values may be given by complex numbers. Addition and multiplication are subject to the rules which apply to complex numbers. When necessary, the magnitude of the potential vector, $E$, is indicated thus: $|E|$.

### VECTOR VOLT-AMPERES

If a sinusoidal electromotive force, represented by the vector, $E$, is applied to a circuit and the resulting current is also sinusoidal and is represented by the vector, $I$, the vector volt-amperes, $\underset{\smile}{E}I$, are

$$\underset{\smile}{E}I = P + jQ \text{ (See footnote 2.)} \qquad (1)$$
$$P = |E| \times |I| \cos\theta \text{ watts}$$
$$Q = |E| \times |I| \sin\theta \text{ vars}$$

where $\theta$ is the phase angle by which the current leads the electromotive force. $P$ and $Q$ are the active and reactive powers. This expression, $\underset{\smile}{E}I$, for the vector volt-amperes is a very useful one in circuit analysis. It is a non-rotating vector and is in this respect quite different from the rotating vectors which represent the potential and current. Due to its non-rotating character, vector volt-amperes due to a potential and current of one frequency may be added to the vector volt-amperes due to a potential and current of another frequency, and the result will be a fixed vector. It must

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[2] $\underset{\smile}{E}$ is the conjugate of $E$ with respect to the horizontal axis, *i. e.*, the axis of reals. If

$$E = |E|\,\overline{/\omega t}$$
$$\underset{\smile}{E} = |E|\,\overline{/-\omega t}$$

and $$I = |I|\,\overline{/\omega t + \theta}$$

Then $$\underset{\smile}{E}I = |E| \times |I|\,\overline{/\theta}$$
$$= |E| \times |I|\,(\cos\theta + j\sin\theta)$$
$$= P + jQ$$

where $$P = |E| \times |I| \cos\theta \text{ watts}$$
$$Q = |E| \times |I| \sin\theta \text{ vars}$$

be borne in mind that reactive power as well as active power depends only upon potentials and currents of the same frequency. If several frequencies are present simultaneously, both of these powers are computed for each frequency separately as if the other frequencies did not exist; that is, potential of one frequency and current of another frequency produce neither active nor reactive power.

### TOTAL VECTOR VOLT-AMPERES

There is an important mathematical theorem in circuit analysis of which, apparently, no formal proof has been given. It is, that the sum of the vector volt-ampere inputs to the individual branches of any network whatsoever equals the vector volt-ampere input at the terminals of the network. In the general case, when the potentials and currents are non-sinusoidal, each harmonic order may be considered separately, since they have no effect upon each other in the vector volt-amperes. First it is evident that the total vector volt-ampere input at the terminals of any series or parallel combination is not affected by replacing the combination by its equivalent single circuit. The key to the proof, however, is the star-mesh transformation.[3] It may be shown that the total vector volt-ampere input at the terminals of any star is not affected by replacing the star by its equivalent mesh. In these replacements the impedance of any branch of the original network at the frequency being considered is the *ratio of the potential vector to the current vector* for that branch and at the frequency considered. In the analysis it is only necessary to specify what these ratios are and not to describe how they may be obtained by physical circuits. In the case of non-linear circuits it may be necessary for these impedances to assume values of zero and infinity. If in any branch there is a harmonic component of current without any corresponding component of potential, the coefficient, $z$, for that branch is zero; and similarly, if there is a harmonic component of potential without a corresponding component of current, the coefficient, $z$, for the branch is infinite. The series, the parallel, and the star-mesh transformations are still valid even in these extreme cases.

By means of these transformations any network can be reduced to a single circuit or circuits connecting its input terminals. This process does not alter the total vector volt-amperes, and thus the theorem is proved in the case of a single frequency. Since it is true for one frequency it is also true in the general case where the potentials and currents are non-sinusoidal. Thus the theorem may be expressed in the general formula:

Total vector volt-ampere ($E_0 I_0$) input to any network is

$$\underset{\wedge}{E}_0 I_0 = \sum_{h=1}^{h=m} \sum_{k=1}^{k=n} \underset{\wedge}{E}_{hk} I_{hk} \qquad (2)$$

where $h$ is the harmonic order of potential and current and there are $n$ branches in the network. The summation is made for all of the harmonic orders in all of the branches.

The foregoing proof involves only the potential and current vectors and no restriction is placed upon them except that they must obey the two Kirchhoff laws that $\Sigma E$ about any closed loop is zero and that $\Sigma I$ at any point is also zero. The real part of the total vector volt-amperes to any branch, $\Sigma \mid E_h \mid \times \mid I_h \mid \cos \theta_h$, is the total power supplied to that branch. It is not illogical then to name the imaginary part, $\Sigma \mid E_h \mid \times \mid I_h \mid \sin \theta_h$, the reactive power supplied to that branch. It should be emphasized that this definition of reactive power is based on the relation of the *terminal* potential of any branch and the *current* in the branch. It in no way inquires into the cause of this relation and so does not attempt to correlate the "reactive power" and any of the physical reactions within the branch. The physical concept of (active) power is perfectly definite. Unfortunately, however, there is, apparently, no general physical concept of reactive power. It is true that reactive power is due to the displacement between the potential and current produced by the physical characteristics of the circuit. The displacement is frequently caused by the magnetic and electric fields and thus there has grown a belief that there is a direct relation between the reactive power and the power delivered to, or energy stored in, these fields. Since the displacement may be produced by other physical characteristics, the physical conception of reactive power based on the magnetic and electric fields cannot be general. Moreover, as we shall presently show, this conception may lead to erroneous conclusions. Reactive power is fundamentally a mathematical quantity which is useful in circuit analysis. It is for this reason that its definition has been labeled "mathematical."

### POWER PULSATION

Before we attempt to identify the reactive power defined in this manner with any physical characteristic of the circuit, there is a variation of the mathematical theorem that is worth while considering. It will be noticed that the theorem holds equally well when the vectors, $E$, are substituted for their conjugates; that is, for any single frequency we may write:

$$E_0 I_0 = \sum_{k=1}^{k=n} E_k I_k \qquad (3)$$

The product $EI$ has a particular and useful significance. If the potential across any branch is:

$$e = \sqrt{2} \mid E \mid \sin (\omega t + \alpha)$$

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[3] "Direct Capacity Measurement," G. A. Campbell, *Bell Sts. Tech. Jour.*, v. 1, July 1922, p. 18.

"A New Network Theorem," A. Rosen, *Jour. I.E.E.*, v. 62, 1925.

and the current in this branch is:

$$i = \sqrt{2}\,|I|\sin(\omega t + \alpha + \theta)$$

then the instantaneous power, $p$, is:

$$p = |E| \times |I| \cos\theta - |E| \times |I| \cos(2\omega t + 2\alpha + \theta)$$

or

$$p = |E| \times |I| \cos\theta - |E| \times |I| \sin(2\omega t + 2\alpha + \theta + 90^\circ)$$

Thus the double frequency portion of the instantaneous power can be represented by the vector product, $-jEI$. (See footnote 4.) This double frequency portion of the power will be called the power pulsation and it will be represented by the letter, $S$, (sinusoidal). Thus:

$$S = -jEI \tag{4}$$

Equation (3) may then be written

$$S_0 = \sum_{k=1}^{k=n} S_k = -j \sum_{k=1}^{k=n} E_k I_k \tag{5}$$

Since the total instantaneous power input is equal to the sum of the instantaneous powers absorbed by the various branches of the network, and since the same relation also holds for the average values of the power, the total power pulsation must be equal to the sum of the power pulsations in the various branches of the network. If there are harmonics present in the potentials and currents, the instantaneous power will contain terms that are the product of potentials and currents of different frequencies, and thus equation (3) cannot be extended to include the case where harmonics are present, as can be done with equation (2) for the vector volt-amperes.[5]

When the potentials and currents are both sinusoidal and of the same frequency, equations (2) and (5) can be combined in the following manner to obtain a check on the circuit calculations: Let

$$E_k = E_k' + jE_k''$$

and

$$I_k = I_k' + jI_k''$$

And similarly let

$$E_0 = E_0' + jE_0''$$

and

$$I_0 = I_0' + jI_0''$$

Then

$$E_k I_k = E_k' I_k' - E_k'' I_k'' + j\,(E_k' I_k'' + E_k'' I_k')$$

Also

$$\underset{\wedge}{E}_k I_k = E_k' I_k' + E_k'' I_k'' + j\,(E_k' I_k'' - E_k'' I_k')$$

If these results are substituted in equations (2) and (5) it at once follows that:

$$E_0' I_0' = \Sigma\, E_k' I_k'$$
$$E_0'' I_0'' = \Sigma\, E_k'' I_k'' \tag{6}$$
$$E_0' I_0'' = \Sigma\, E_k' I_k''$$

and

$$E_0'' I_0' = \Sigma\, E_k'' I_k'$$

The usefulness of these relations is apparent when we consider a typical problem. Let us suppose that the current input to a network due to the application of a potential $E_0' + j0$ is $I_0' + jI_0''$. Further let us suppose that in the solution of this problem we have determined the complex expressions for the potential and current for each branch of the network. The sum of the products of the imaginary component of each of these potentials and the real component of the corresponding current over the whole network should be zero, as shown by the fourth relation. The other relations are interpreted in a similar manner.

There is another important relation that results from this "mathematical" definition of reactive power. The sum of the squares of the active and reactive powers is in general equal to the square of the effective volts multiplied by the square of the effective amperes only when the potential and current are sinusoidal and of the same frequency. When there are harmonics present in either the potential or current, or in both simultaneously, this relation is in general not true. Or it may be stated that the magnitude of the vector volt-amperes, *viz.*, $\sqrt{P^2 + Q^2}$ does not equal the product of the effective volts and the effective amperes when there are harmonics present. For example, it would be found when testing a power transformer on open circuit that the difference between these quantities might well be as much as 8 per cent.

## PHYSICAL CONCEPT OF REACTIVE POWER

We will now examine three of the physical concepts of reactive power which connect it with the electric and magnetic fields.

*I. Concept of Instantaneous Reactive Power.* We shall define the instantaneous value of the reactive power supplied to a magnetic field by the electric circuit as the product of the instantaneous value of the current in the circuit and the instantaneous value of the electromotive force generated in the circuit by the time variation of the magnetic field. Similarly, the instantaneous value of the reactive power supplied to an electric field, *i.e.*, to a perfect condenser, equals the product of the instantaneous value of the current in the condenser and the instantaneous value of the potential across the terminals of the condenser. In other words, the instantaneous value of the reactive power is the time variation of the instantaneous value of the energy stored in the magnetic and electric fields. If the instantaneous value of the reactive power is zero, the stored energy is constant. If the potential and current are both sinusoidal the instantaneous reactive power is also sinusoidal but of double frequency. Care must be

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[4]
$$\begin{aligned} EI &= |E|\,\underline{/\omega t + \alpha}\;|I|\,\underline{/\omega t + \alpha + \theta} \\ &= |E| \times |I|\,\underline{/2\omega t + 2\alpha + \theta} \\ jEI &= |E| \times |I|\,\underline{/2\omega t + 2\alpha + \theta + 90^\circ} \end{aligned}$$

[5] The mathematical formula can be extended to include harmonics, but it cannot be interpreted as pulsating power, since the pulsating power will contain terms which are the product of potential of one frequency and current of a different frequency.

observed in distinguishing between the terms "instantaneous value of reactive power" and "reactive power," (I.D).[6] The former varies with the time while the latter does not. In this respect the former corresponds to the instantaneous power input to a circuit, while the latter corresponds to the average or active power input.

If a sinusoidal potential is impressed on a series circuit of resistance $R$ and reactance $X$ the maximum value of instantaneous power input to the electric and magnetic fields equals the reactive power input as internationally defined. This fact may give rise to a prevalent belief that when a circuit is adjusted so that the reactive power (I.D.) input at the terminals is zero, *i.e.*, so that the terminal power factor is unity, the instantaneous value of the total reactive power is also zero, *i.e.*, the total stored energy in the electric and magnetic fields is constant. Unfortunately, however, this is not generally true in single-phase circuits except in one special case which we will presently describe. Neither is it true in polyphase circuits. If, for example, a symmetrical polyphase circuit has impressed upon it symmetrical potentials, the total instantaneous reactive power input is always zero, regardless of the power factor at which the circuit is operating. That is, the total stored energy is constant just as the total instantaneous power input to the circuit is constant.

Let us see what limitation must be imposed in the single-phase case for the belief to be true. Consider an $R$, $L$, $C$ network having two points of entry only, across which is impressed a sinusoidal electromotive force. Every inductance is assumed to have resistance associated with it, although the condensers may be assumed to be perfect.

Theorem: If this network is adjusted so that the total instantaneous power input to its electric and magnetic fields is zero, the currents in all of the branches of the network are in time phase.

Proof: The instantaneous power input to a resistance $R$ which is carrying a current

$$\sqrt{2}\,|\,I\,|\sin(\omega t + \alpha) \text{ is:}$$

$$p_R = R\,|\,I\,|^2 - R\,|\,I\,|^2 \cos 2\,(\omega t + \alpha)$$

If the same current flows through an inductance $L$ the instantaneous power input to the magnetic field is:

$$p_L = \omega L\,|\,I\,|^2 \sin 2\,(\omega t + \alpha)$$

If the current flows through a capacitance $C$, the instantaneous power input to the electric field is:

$$p_C = -\frac{1}{\omega C}\,|\,I\,|^2 \sin 2\,(\omega t + \alpha)$$

For the same reason that it is proper to represent this current by the rotating vector $I$ it is also proper to represent the double frequency portion of the power input to the resistance by the rotating vector $-jRI_R^2$ and the power input to the magnetic or electric field by the rotating vector $XI_X^2$, where $X$ is positive for inductance and negative for capacitance.[7] $I_R$ and $I_X$ are the rotating vectors which represent the currents in the resistance, $R$, and the reactance, $X$, respectively.

Therefore the double frequency portion of the power input at the terminals of the network may be represented by a rotating vector $S_0$ of the form

$$S_0 = \Sigma\,(-jRI_R^2 + XI_X^2) \qquad (7)$$

or

$$S_0 = -j\,\Sigma\,(RI_R^2 + jXI_X^2)$$

Compare this with equation (**4**).

The vector volt-ampere input at the terminals of the network is

$$P_0 + jQ_0 = \Sigma\,(R\,|\,I_R\,|^2 - jX\,|\,I_X\,|^2)$$

Note that while $S_0$ is obtained by a vector summation, $P_0$ is obtained by a numerical summation since $R$ is always positive and $Q_0$, by an algebraic summation since $X$ may be either positive (inductive) or negative (capacitive). Now it is well known that the amplitude of the double frequency power input equals the magnitude of the vector volt-amperes, that is:

$$|\,S_0\,| = \sqrt{P_0^2 + Q_0^2}$$

If the network is adjusted so that the total instantaneous power input to the magnetic and electric field is zero,

$$\Sigma\,XI_X^2 = 0$$

and

$$S_0 = -j\,\Sigma\,RI_R^2$$

Thus the magnitude of the vector sum $\Sigma\,RI_R^2$ equals the square root of the sum of the squares of the magnitudes of the numerical sum $\Sigma\,R\,|I_R\,|^2$ and of the algebraic sum $\Sigma\,X\,|\,I_X\,|^2$.

Since the vector sum of any number of vectors may be equal to but not greater than the numerical sum of their magnitudes, it follows that not only

$$|\,\Sigma\,RI_R^2\,| = \Sigma\,R\,|\,I_R\,|^2 \qquad (8)$$

but also

$$Q_0 = \Sigma\,X\,|\,I_X\,|^2 = 0$$

Therefore the reactive power $Q_0$ at the terminals is zero, and since the vector and numerical sums are equal, as shown by equation (**8**), the currents in all of the branches of the network which contain resistance are in time phase.

Since in the case we are considering the reactive power input, $Q_0$, at the terminals is zero, the input current, $I_0$, is in phase with the applied potential, $E_0$, and the network is equivalent[8] to resistance

$$\frac{E_0}{I_0} = R_0.$$

Thus the double frequency power input, $-jR_0I_0^2$, equals

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[6] International definition.

[7] The square of a vector, $V$, is a vector, $V^2$, whose magnitude is the square of the magnitude of $V$ and whose phase angle is always double the phase angle of $V$. The speed of rotation of $V^2$ is thus twice the speed of rotation of $V$.

[8] In the steady state and at the given frequency.

$-j\sum RI_R^2$. From this it follows that all of the currents in the branches containing resistance are in phase with the input current at the points of entry.

It remains to consider those cases in which some of the branches of the network may not contain resistance. In any actual network every inductance would be associated with resistance, but it is often assumed that the capacitances are perfect, *i.e.*, without series resistance. Consider a network some of whose branches consist wholly of capacitance. When the currents flowing into any network and the impedances of its branches are known, the currents in all parts of the network are determined by applying the two Kirchhoff principles. Apply these principles to the capacitive portion of the network. The currents flowing into these capacitive branches will come either from branches containing resistance or directly from one or both of the points of entry. Since all of these input currents to the portion of the network under consideration are in time phase, and since all of the branches of this portion of the network have impedances of the form

$$-j\,\frac{1}{\omega C},$$

it follows that all of these capacitive currents will be in time phase with the input current. Thus the theorem is generally true for all actual networks.

We have therefore proved that if a single sinusoidal electromotive force is impressed on any actual $R$, $L$, $C$ network which is adjusted so that it operates at unity power factor the total instantaneous input to its electric and magnetic fields is zero only when the currents in all of the branches of the network are in time phase. Since such a network may be adjusted for unity power factor without having all of the currents in time phase it follows that there can be no general relation between the reactive power as defined by international agreement and the instantaneous value of the power input to the electric and magnetic fields.

Another interesting point is illustrated by the simple circuit shown in Fig. 1($a$). The resistance and reactance of the coil are equal and the reactances of the condensers are each one-half of the reactance of the coil. The vector diagram showing the potentials and currents is in Fig. 1($b$). From this are derived the vectors,

$$-\frac{1}{\omega C_1}I_{c1}^2,\ -\frac{1}{\omega C_2}I^2_{c2},\ \text{and}\ \omega L I_L^2$$

which represent the instantaneous reactive powers in the condensers and inductance. (See equation (**7**).) In this case the maximum value of the instantaneous reactive input at the terminals equals the reactive power (I.D.) input even though the currents are not in phase. Note, however, that the instantaneous reactive power input to $C_1$ is equal in magnitude, but in exact time opposition, to the instantaneous reactive power input to $C_2$; that is, it might reasonably be said that there is a direct interchange of energy between these condensers so as to maintain their total energy constant. Since the instantaneous reactive power input to the condensers is zero, the total instantaneous reactive input at the terminals equals that taken by the coil. From this point of view it would be reasonable to conclude that the reactive power input at the terminals is inductive, from which it would follow that the input current lags the applied potential. This is an entirely erroneous conclusion, since the input current leads the applied potential as is shown in the vector diagram.

We have attempted to obtain a physical conception of reactive power by associating it with the instantaneous power input to the electric and magnetic fields. We have clearly shown that the sum of the instantaneous values of reactive power in the different branches of a network may give no indication as to the value or character of the reactive power (I.D.) at the input terminals to the network.

Imagine the confusion of a student who is taught that sinusoidal electromotive forces or currents must be combined with due regard to their phase relations, while reactive powers, which he is also taught to think of as sinusoidal quantities, are combined without regard to their phase relations. In view of this it seems wise to discard this conception of reactive power entirely, at least when combining the reactive powers in a number of branches.

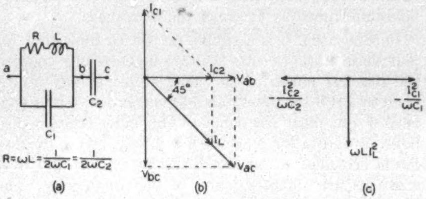


FIG. 1—SIMPLE CIRCUIT ($a$), POTENTIAL AND CURRENT VECTORS ($b$), AND VECTORS ($c$) WHICH REPRESENT THE INSTANTANEOUS REACTIVE POWER IN THE CONDENSERS AND INDUCTANCE

*II. Concept of Maximum Value of Stored Energy.* The reactive power might be associated with the maximum value of the stored energy. Consider two reactive coils connected in parallel. The total reactive power is the numerical sum of the reactive powers in the two branches, but the maximum values of the stored energy may occur at different times inasmuch as the currents may not be in time phase. Thus the maximum stored energy in the magnetic fields may not be equal to the sum of the maximum values of the stored energy in the individual fields. Thus this conception of reactive power is also open to the same objection as that we have already discussed.

*III. Concept of Average Stored Energy.* The reactive power might be associated with the average value of the stored energy, provided this stored energy is given a positive value when the current in the circuit leads the potential across the circuit, and is given a negative value when the current lags the potential difference. The very obvious advantage of using the mean value of the stored energy is that it has no phase relation associated with it, that is, if we do not regard plus and minus signs as indicating a phase relation. If a circuit contains a series inductance of constant value, $L$, and is carrying a sinusoidal current, $i = \sqrt{2}\,|\,I\,|\,\sin \omega t$, the instantaneous value of the stored energy is $\frac{1}{2} Li^2$. The mean value of this stored energy is $\frac{1}{2} L \left| I \right|^2$. Now the reactive power in this case is $Q = \omega L \left| I \right|^2$, that is, the reactive power is the mean value of the stored energy multiplied by $2\omega$. Exactly the same relation holds if the circuit contains capacitance and if the current is sinusoidal. We now have a physical conception of reactive power that holds for any single-phase static network, *i.e.*, having only two points of entry, in which all of the electromotive factors and currents are sinusoidal. That is, the reactive power at the terminals is the algebraic sum of the average values of the energy stored in the electric and magnetic fields multiplied by $4\pi$ times the frequency.

Furthermore, it is a simple matter to show that for polyphase static circuits that are magnetically coupled the reactive power is the mean stored energy multiplied by $2\omega$ if the potentials and currents are sinusoidal and of the same frequency. The same relation also holds for a rotating machine like a polyphase induction motor provided the potentials and currents in the stator windings are sinusoidal and of one frequency. The mean value of the stored magnetic energy, however, does not account for the reactive power input to a synchronous motor since the power factor at which the motor operates is controlled by the field excitation and may range from lagging to leading.

If a non-harmonic current, the effective values of whose harmonic components are $I_1$, $I_2$, and $I_3$, flows through a constant inductance $L$, the mean value of the stored energy is

$$\frac{1}{2} L \left(I_1^2 + I_2^2 + I_3^2\right).$$

If the definition for reactive power is extended to include harmonics as we have suggested the reactive power in this case is $\omega L \left(I_1^2 + 2I_2^2 + 3I_3^2\right)$. It thus bears no direct relation to the mean stored energy as it did with sinusoidal currents.

Finally, in all of those cases where, due to the presence of magnetic material, the inductance is a function of the current, it is not possible to determine the value of the mean stored magnetic energy inasmuch as the physical phenomena involved are not understood in any quantitative manner. Thus in these cases there is no determined relation between the reactive power and the mean stored energy.

If reactive power is measured by a meter of the dynamometer type in which the potential circuit consists wholly of inductance, the instrument is subject to frequency errors. Furthermore the instrument indicates the mean value of the stored magnetic energy if there are harmonics present and if the inductances in the network are independent of current strength. In fact, the definition of reactive power might be based on the meter reading. If this were done, however, the generalized mathematical concept of reactive power that has been here developed would have to be discarded.

*Conclusion.* Reactive power, as defined by international agreement, is fundamentally a mathematical quantity. At present it is based upon an assumption of sinusoidal potentials and currents. This limitation of a sinusoidal wave form can be removed and the definition will then correspond to that for active power. We would then have a truly scientific definition. If this were done the generality of the mathematical definition of reactive power and its use in circuit calculations would far outweigh any other consideration. Reactive power is due to some physical characteristic of the circuit which causes a phase displacement between the potential across the circuit and the current in it. Constant inductance and capacitance will produce this effect. It may also be produced by the electric arc or by resistance that varies with the current strength due to heating. In rotating synchronous machines the phase displacement can be controlled by the relative strength of the field poles. In general, however, reactive power cannot be said to equal any one definite physical quantity. The best physical concept that we have is based upon the mean value of the stored energy, but in determining this mean value the energy stored in an inductance must be counted of opposite sign to that stored in a condenser. Furthermore this concept is valid only when the circuit is linear and the impressed potentials are of a single frequency. Any concept based wholly upon the instantaneous value of the stored energy or of the time rate of change of the stored energy will probably lead to great confusion in the mind of the student. It is relatively unimportant that there is no general physical concept of reactive power. Were it defined as a physical quantity that did not prove useful in circuit analysis it would soon be forgotten.

It is important to note that for the purpose of circuit calculations the components of both the active and reactive power for *each* frequency need to be given. The *resultant* active and reactive power for all frequencies *combined* is of little value in circuit calculations.

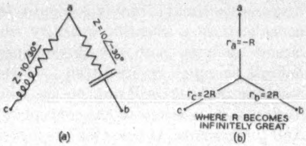
## POWER FACTOR

The general definition of the power factor of a single-phase network is the ratio of the power supplied, $P$, to the product of the applied potential difference, $V$, and the current, $I$. Under all conditions this product is the greatest power that the given effective current, $I$, can produce at the given potential difference, $V$. With this in mind the definition of power factor might be formulated as follows: Power factor is the ratio of the actual power to the greatest power that the given effective current and the given potential can produce. This form of the definition has one possible advantage. It can be extended to the general polyphase case where the applied potentials are not sinusoidal.

In the single-phase case the only load which in general will take the maximum amount of power for a given effective value of the current is a fixed non-reactive resistance. The accepted definition of power factor thus compares the actual load with a non-reactive resistance load, both of which take the same effective value of current at the same potential. When we attempt to obtain a corresponding conception of power factor in a polyphase circuit we must allow the resistances of the different phases of this non-reactive load to take on any value from plus to minus infinity. For example, take the simple three-phase load illustrated in Fig. 2($a$).

If the line potentials are sinusoidal and each has a value of 100 volts, the line currents are 20 amp, 10 amp, and 10 amp. In order to duplicate these line currents and have the branches non-reactive resistances they must have the values indicated in Fig. 2($b$). Although such a condition is physically impossible we may still consider the condition of maximum power for given values of effective currents. For example, the load shown in Fig. 2($a$) takes the greatest possible power for the given values of line currents. The reactive power input to this load is zero.

Fig. 2—Simple Three-Phase Load ($a$), and Non-Reactive Resistances ($b$) Giving the Same Line Current



In the following discussion we shall assume that the currents and potentials are sinusoidal and of the same frequency. First consider a network that has three points of entry. This might be either a three-phase circuit or a three-wire two-phase circuit. The potentials between the successive line conductors are fixed. This determines a triangle of the line potential vectors. Similarly, since the magnitudes of the line currents are also known—by hypothesis—the current vectors also determine a triangle. This triangle may take one of two forms determined by whether the currents are in the same phase order as the line potentials or in the opposite phase order. In either case the maximum value of the power supplied equals the magnitude of the vector volt-amperes, $\sqrt{P^2 + Q^2}$ but the vector volt-amperes are greater when the phase order of the currents is the same as that of the potentials. Thus, in this case of a three-wire circuit, the maximum value of the power that can be supplied by the given potential and currents equals the vector volt-amperes determined on the assumption that the phase orders of the potentials and currents are the same. If it happens that the phase orders of the line currents and line potentials are opposite, the magnitude of the vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$, is less than the maximum possible power for the given system of line potentials and of line currents. This condition may arise when an induction motor is running idly on an unbalanced potential system. All that is necessary is to have an unbalance in the line potentials greater than the ratio of the no-load admittance to the blocked admittance of the motor. The negative-sequence current will then be greater than the positive-sequence current and the phase order of the line currents will be opposite to the phase order of the line potentials. There is thus the possibility that the power factor as determined by the ratio of the actual power to the maximum power for the given line potentials and line currents will not equal the power factor as determined by the ratio of the actual power to the magnitude of the vector volt-amperes.

Let us now consider a network into which currents flow at four or more points; for example, a three-phase circuit with neutral connection, or a four-phase circuit. The line potentials are fixed both in magnitude and in relative phase. Assume for the moment that the phase relations of the line currents are fixed with respect to each other but not with respect to the line potentials. Then, if the phase order of the line currents is the same as that of the line potentials, the maximum power for this particular current polygon is equal to the magnitude of the total vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$. With four or more currents the phase relations of the currents with respect to each other are not fixed by the magnitudes of the currents as they are in a network having three points of entry. The magnitude of the vector volt-amperes, however, depends upon the phase relations of the currents with respect to one another, and there is one particular current vector polygon for which the vector volt-amperes are greater than for any other. Thus the magnitude of the total vector volt-amperes, *viz.*, $\sqrt{P_0^2 + Q_0^2}$ is generally less than the maximum power that can be developed by the given system of line potentials and the given line currents. For example, consider a symmetrical four-phase circuit having line potentials of 100 volts between adjacent conductors and 141.4 volts between alternate conductors. Connect two resistance loads, each of 10 ohms, across opposite pairs of line conductors. The line currents are each 10 amp. The active power is 2,000 watts and the reactive power is zero. The 2,000 watts is the maximum power for this particular current polygon. Now connect four resistances, each of 14.14 ohms across adjacent pairs of line conductors. The line currents are again 10 amp. The reactive power is again zero, but the active power is now 2,828 watts.

The 2,828 watts is not only the maximum power for this current polygon but it is the greatest power that can be developed by any load whose line currents are each 10 amp. If power factor should be defined as the ratio of the actual power to the maximum power that can be developed for the given ampere values of the line currents, the power factor of the first resistance load would be 0.707. This power factor would be the power factor of the load considered from a polyphase standpoint. Considered from the point of view of individual single-phase loads, the power factors are each unity. The first of these loads is unbalanced, and it is probably better to use two factors in describing it, *viz.*, power factor based upon active and reactive power, and unbalance factor based upon symmetrical components. Thus it seems unwise to extend to polyphase circuits the conception of single-phase power factor, that is, that it is the ratio of the actual power to the maximum power for the given potential and current.

## CONCLUSION

We have given definitions for potential, current, and active and reactive power which are independent of wave form and of circuit conditions. In order to use these quantities in circuit analysis when there are harmonics present, it is necessary to know their individual harmonic components. The value of the total or resultant quantity is not sufficient. By definition, single-phase power factor is a blanket factor which covers and so disregards any deviation in wave form from the sinusoidal. Thus it is not a quantity that can be used in circuit analysis when there are harmonics present. If polyphase power factor is defined as the ratio of the power to the magnitude of the vector volt-amperes it is likewise a useless quantity in circuit analysis if there are harmonics present. Furthermore, this definition of polyphase power factor makes it a derived quantity which depends upon the active and reactive power. Even when there are no harmonics present so that power factor may be legitimately used, the circuit calculations are usually simpler if the loads are determined by their active and reactive powers rather than by their power factors. That is, as far as circuit analysis is concerned, power factor is a quantity whose retirement need scarcely be noted.

There is, however, another and important use for power factor. There is a need for just such a blanket factor when specifying the character of power loads from a commercial standpoint, that is, when writing specifications or power rates. In that case it does not seem necessary that power factor should have a rigorous scientific definition such as has been given potential, current, and power, and can be given reactive power. In these quantities we have adequate means for specifying our circuits for the purpose of analysis. On the other hand, it seems best to consider power factor as a purely commercial quantity and to define it accordingly. It may be that the present definitions of single-phase and polyphase power factor are adequate. However, before the definition is written we should decide upon the status of power factor; whether it is to be classed as a scientific quantity like power, for example, or as a commercial quantity like load factor. In making this decision we should frankly recognize that if it is to be considered as a scientific quantity which is useful in circuit analysis, both the single-phase and polyphase definitions must be rewritten. If this is done, the resulting quantity will not, on the whole, be as useful in circuit calculations as the concept of reactive power. And furthermore, in this case the power factor will not be the useful commercial quantity which now appears in specifications and power contracts.

## Discussion

For discussion of this paper see page 779.

# Notes on the Measurement of Reactive Volt-Amperes

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***Synopsis.***—*In the following paper, the character of the quantity known as reactive volt-amperes is first discussed and its dependence on the assumption of a definite type of periodicity is brought out, this in contrast to certain other a-c quantities. It is pointed out that on account of the rather complicated relation that it bears to the flow of energy in an electric circuit serious difficulties are met in its measurement except in the simpler conditions of balanced voltages, in a polyphase circuit, and sinusoidal waves. Two procedures are outlined which though they are not premised on balanced voltages have frequency and wave form limitations.*

*In the latter part of the paper, the relation of the quantity of energy that surges in an a-c circuit in which there is energy storage, to the average flow of energy is considered, and advantages of this conception as a basis for rates are indicated.*

*Finally, it is pointed out that reactive volt-amperes is of the nature of a complementary quantity rather than a specific activity of the electric circuit which when suitably combined with power gives volt-amperes.*

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CERTAIN of the quantities used to describe the phenomena associated with alternating currents require the postulation of a definite type of periodicity or a definite frequency in order to give them meaning. Among these are phase angle and reactive volt-amperes. Even with an almost haphazard character of oscillation, an alternating current may have a definite root-mean-square value provided the averaging is carried over a sufficient interval, but in stating a value of reactive volt-amperes, a definitely ordered frequency must be assumed.

In the measurement of reactive volt-amperes or reactive volt-ampere-hours, we are concerned with quantities the definitions of which are dependent on the assumption of periodicity and which consequently can have definite values only when considered over intervals long enough to establish a definite character to that periodicity. In the ordinary case in which the frequency is constant and the measured quantities and their components show simple sinusoidal variation, the procedure for measurement need not be very complicated though the extreme simplicity of power measurement apparently cannot be attained. Most commercial devices for the measurement of reactive volt-amperes are designed on the assumption that the complications arising from a complexity in wave form may be neglected.

If the problem at hand happens to be to measure a particular type of quantity, it is useful to know something more about that quantity than the equation that defines it. The equation may be the residue remaining after numerous terms, that must be represented in the mechanism for measurement, have been eliminated.

In the measurement of energy with the ordinary watthour meter, we integrate, with respect to time, the instantaneous products of current and voltage. In the measurement of power, using the ordinary wattmeter, we progressively average values that are obtained by integration. In the former, the integration is continued indefinitely; in the latter, the integration and averaging occur by reason of the inertia of the deflecting member of the instrument. In both measurements, we are dealing from instant to instant with components of power, *i.e.*, instantaneous current and instantaneous voltage that are readily accessible in the electrical circuit; the measured quantities have a meaning however short the chosen interval.

In a single phase electric circuit containing inductance or capacity, in each half cycle there is a storage and release of energy which is determined by the changing instantaneous values of current and voltage. An oscillographic wattmeter shows this as an ebb and flow of power in the circuit. In a balanced polyphase circuit considered as a whole, the flow of energy may be at a perfectly uniform rate because the storage of energy in one part of the circuit is exactly balanced by the release of energy in another part; yet each conductor is the scene of a pulsation of energy.

Assume sinusoidal voltage and current according to equations (**1**) and (**2**). Their product gives the power equation (**3**) which transformed, shows this product to be equivalent to the sum of two terms, equations (**4**) and (**5**). One term is an average value of the power and so independent of time. The second is a double frequency pulsation of power of which the average value over an integral number of half cycles is zero and which consequently closely approximates zero over any sufficiently long interval of time.

If the time origin be so chosen that it falls exactly midway between the time of zero value of voltage and the time of zero value of current, the very simple form shown in equation (**9**) results.

Instead of expressing the relation of the sinusoidal pulsation of power to the time origin as an angle, we may show this pulsation as the sum of two sinusoidal components, one passing through maximum, the other through zero value at time zero (equation (**6**) ). If also, we chose zero time to coincide with the time of zero value of either voltage or current, equations (**7**) and (**8**) result. These have the peculiarity that the coefficient

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EQUATIONS 1 TO 9

$$e = E_m \sin(\omega t - \varphi_e) \tag{1}$$

$$i = I_m \sin(\omega t - \varphi_i) \tag{2}$$

$$p = ei = E_m I_m \sin(\omega t - \varphi_e)\sin(\omega t - \varphi_i) \tag{3}$$

$$= \frac{E_m I_m}{2}\cos(\varphi_i - \varphi_e) - \frac{E_m I_m}{2}\cos(2\omega t - \varphi_e - \varphi_i) \tag{4}$$

Let $\varphi = \varphi_i - \varphi_e$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}\cos(2\omega t - [\varphi_e + \varphi_i]) \tag{5}$$

$$= \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}[\cos(\varphi_e + \varphi_i)\cos 2\omega t + \sin(\varphi_e + \varphi_i)\sin 2\omega t] \tag{6}$$

If $\varphi_e = 0$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}(\cos\varphi\cos 2\omega t + \sin\varphi\sin 2\omega t) \tag{7}$$

Is $\varphi_i = 0$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}(\cos\varphi\cos 2\omega t - \sin\varphi\sin 2\omega t) \tag{8}$$

From equation (5) if $\varphi_e = -\varphi_i$

$$p = \frac{E_m I_m}{2}\cos\varphi - \frac{E_m I_m}{2}\cos 2\omega t \tag{9}$$

$$= EI(\cos\varphi - \cos 2\omega t) \tag{9a}$$

of the cosine term of power pulsation is the same as the first term of the equation, *i.e.*, the value of average power. As is also true in equation (6), the sum of the square of the coefficient of the double frequency sine term and the square of the coefficient of the double frequency cosine term is $(E_m^2 I_m^2)/4$ or in rms quantities $E^2I^2$.

As indicated by these several equations, the content of the components that are due to the pulsation of energy is dependent on the choice of time origin. It is only when the time origin happens to coincide with the time when either the current or voltage wave passes through zero value that the terms in the power equation correspond to, and entirely separate, energy dissipation and energy surging; but the first term always gives average power.

When the current and voltage waves contain harmonics, the average power is the sum of the averages of the power contributed by the harmonics individually, *i.e.*, in the average power, there are no terms due to the product of components of different frequency although such products must occur in the equation for the instantaneous power. So, if we would express the surging of energy due to the harmonics separately, we must in general choose a different time origin for each harmonic. Otherwise, pulsation of power that corresponds to dissipated energy can no longer be separated from the pulsation due to energy stored.

In equations (7) and (8), $\frac{1}{2}E_m I_m \cos\varphi$ and $\frac{1}{2}E_m I_m \sin\varphi$ are coordinate insofar as they are the coefficients of two arbitrarily chosen components of the pulsation of power. On the other hand, $\frac{1}{2}E_m I_m \cos\varphi$ as a measure of the average value of power has no corresponding term in $\sin\varphi$ in the power equation.

We may assume a quantity $\frac{1}{2}E_m I_m \sin\varphi$ analogous to $\frac{1}{2}E_m I_m \cos\varphi$. This is a quantity such that its square when added to the square of the average power gives a quantity in $E_m$ and $I_m$ independent of the phase angle $\varphi$. In rms quantities, we have $(E^2I^2\cos^2\varphi + E^2I^2\sin^2\varphi)^{1/2} = EI$.

Using now rms quantities, $EI\cos\varphi$ has a real existence in the circuit in that it can manifest itself as a measure of the reaction between simultaneously occurring fields, the one due to the current in the circuit and the other produced by a current proportional to the electromotive force.

In contrast, $EI\sin\varphi$ may be looked upon as involving the concept of memory or prediction, *i.e.*, memory + or − depending on the viewpoint.* To be more specific: $EI\sin\varphi$ is the average value of products of instantaneous values of current each multiplied by that value of voltage that existed in the circuit 1/4 cycle earlier. In a 60-cycle circuit, each instantaneous current value must be multiplied by the value of voltage that existed 1/240 sec earlier. If the current and voltage waves contain harmonics, each harmonic must be considered separately, *i.e.*, the instantaneous values of fundamental frequency current must be multiplied by the value of fundamental frequency voltage that existed 1/4 cycle earlier. Each instantaneous value of third harmonic current must be multiplied by the value of third harmonic voltage that occurred 1/12 of a fundamental cycle earlier, etc. In a 60-cycle circuit containing fifth and seventh harmonics, products of pairs of quantities separated in time by intervals of 1/240, 1/1,200, and 1/1,680 sec, respectively, must be secured. Herein doubtless lies the practical difficulty of realizing a theoretically correct procedure in the measurement of reactive volt-amperes or reactive volt-ampere-hours, for mechanisms that in effect have discriminating memories, or something equivalent must be arranged to multiply, sum, and average quantities that have no simultaneous existence.

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*It is very desirable that a convention in regard to sign should be adopted. It is convenient usually to assume inductive reactive volt-ampere to be negative. Reasons for this convention, discussed from the geometrical viewpoint, are briefly given in Appendix II.

It may be pointed out that each instantaneous product that goes to determine $EI \sin \varphi$ is related simply by the numerical ratio $\tan \varphi$ with the corresponding element which determines $EI \cos \varphi$. However, $\varphi$ cannot have a valid meaning unless intervals of time sufficient to establish a definite periodicity can be taken into account which brings us again to the history, *i.e.*, memory of what has been happening in the circuit.

In contrast, $p = ei$ is the instantaneous value of the power whatever functions of time may represent $e$ and $i$. In a-c measurements, we are most frequently interested in average power, *i.e.*, power averaged over an integral number of half cycles or over a time so long that the variation of power within a single half cycle may be neglected.

The relation $\frac{d}{d\varphi} \cos \varphi = - \sin \varphi$ suggests a possible approach, but the quantities, current and voltage, are sine functions of time and therefore their derivatives with respect to time (which could easily be made use of in a measuring device) are proportional to frequency, while $EI \sin \varphi$ is independent of frequency. Indeed if the frequency can be assumed to be constant and the current or voltage wave simply sinusoidal, we may use the derivative of the voltage (represented by the current flowing in a highly inductive derived [capacitive] circuit) to excite the potential circuit of an otherwise, standard wattmeter, and thereby secure a measurement of reactive volt-amperes. Harmonics, however, are represented in the reading of such an instrument as 3, 5, 7, etc., times their real contribution, or if inductive reactance be used, but 1/3, 1/5, 1/7, etc., of their proper values appear.

In a symmetrical polyphase circuit where the voltages or currents are simple sinusoidal functions of the time, the simplest way to get a cosine function voltage for the measurement of reactive volt-amperes, to replace the sine function voltage used in the measurement of power, is by cross connections or cross transformations of the polyphase voltages.

If the voltages are not symmetrical or at least if they do not maintain permanently an exact relation, properly displaced currents to represent the desired voltages may be obtained by the use of resistances together with capacitances as principal components of the voltage circuits of induction meters or by the use of reactive coils in the voltage circuits of electrodynamic types of meters or indicating instruments. This arrangement is equally applicable to single phase circuits and has the advantage that for a definite frequency the potential circuit current is entirely independent of any variations that may occur in the relations of voltage or phase of the polyphase circuit as a whole. It has the disadvantage that currents flowing in these circuits instead of varying inversely with the frequency as they should in the induction meter, or of remaining independent of frequency as they should in the electrodynamic types of apparatus, follow laws which cause errors proportional to the changes of frequency to appear. The corresponding energy and power meters give readings only slightly, or practically not at all, influenced by change of frequency.

When only small changes of frequency are involved, it is possible to effect almost perfect frequency compensation by using capacitive and inductive circuits in parallel, but if irregularities of wave form are present, serious errors may be made to appear by frequency compensations of this general type.

Another procedure that has much to recommend it is to introduce phase displacements in both current and voltage circuits; for instance, a 45-deg advance in the one and a 45-deg retardation in the other. To do this successfully requires great care in design for, in general, current circuits must be suitable for wide ranges of current; this requires that any reactances used in the current circuits shall have characteristics almost wholly uninfluenced by any iron that may be used.

In the discussion that has been given so far, the difficulties connected with irregular wave forms have been mentioned only incidentally. It is probably true that the occurrence of large errors in the measurement of reactive volt-amperes or reactive volt-ampere-hours by reason of complex wave form is infrequent. This is because the simultaneous occurrence of greatly distorted current and voltage waves is unusual.

If we are dealing with a polyphase circuit and make use of cross-phase connections to secure the displaced phase of voltage for reactive measurement, we find this condition: Assuming the voltage source so chosen that the fundamental is 90 deg behind that of the corresponding voltage used for power measurement, the third harmonic voltage will be displaced 3 x 90 deg backward, which is equivalent to 90 deg ahead, the 5th 90 deg behind, the 7th 90 deg ahead and so on. If there is any reactive volt-ampereage due to these harmonics, the amount due to the 5th, 9th, etc., will be properly added, while that due to the 3rd, 7th, 11th, etc., will be subtracted when it should be added.

If a 10 per cent seventh harmonic voltage were accompanied by a 90-deg displaced current of 5 per cent, the incorrect sign that would be given to the seventh harmonic contribution in the reactive volt-amperes would result in a 1 per cent error. But a 10 per cent harmonic in voltage is not met in modern generators. Even a large harmonic of current unless accompanied by an appreciable voltage of the same frequency contributes nothing to either the average power or to polyphase reactive volt-amperes, although they do contribute to the volt-amperes as measured in single-phase circuits.

If the voltages of the polyphase circuit are unbalanced or if we are concerned with single-phase measurement, the cross-phase arrangement for securing displaced phase excitation for the voltage circuits of meters or instruments is unsuitable or impossible. If the frequency is constant, recourse may be had to the use of altered potential circuits as already discussed. The substitution of resistances, or resistances and capacities, for reactances in the potential circuits of induction meters tends to exaggerate the contribution of the harmonics; the substitution of reactance for resistance in the potential circuit of an indicating instrument tends to minimize their effect. The reasons may readily be seen: In the induction meter the voltage circuit excitation should vary inversely as the frequency so that the eddy current strength may remain independent of frequency, but with the equivalent of a non-inductive circuit, the current in such a potential circuit will be independent of frequency and a seventh harmonic eddy current, for instance, would be seven times too large. If, however, the seventh harmonic of current is small, the error might be unimportant.

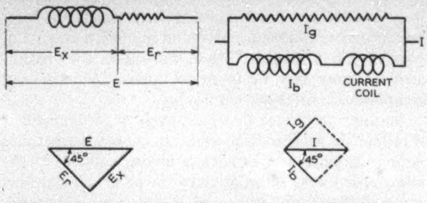

Fig. 1—Circuits of One Form of Reactive Volt-Ampere-Hour Meter and Associated Vector Relations at Frequency *N*

In the indicating instrument with an inductive potential circuit, components due to the harmonics become proportionately too small, *i.e.*, instead of being independent of the frequency, they are inversely proportional thereto.

It is possible to imagine branched circuits, each branch resonant to a particular harmonic, the whole proportioned to give substantially correct current values for each of the harmonics at a chosen frequency, but the phase relations would be completely unstable and so the arrangement appears unusable.

If the potential circuit of an induction meter is made up of non-inductive resistance in series with the customary inductive resistance and the current circuit, supplemented with additional inductance if necessary, is shunted by a non-inductive resistance, (Figs. 1 and 2) the various values of these circuit elements may be so chosen that the difference between the displacements of the currents in the potential and current circuits becomes zero instead of the customary 90 deg. This relation if true for any selected frequency is true for all frequencies when the inductive branch is pure inductance.

If at fundamental frequency, the displacement of the currents which represent voltage and current are each 45 deg from the voltage and current respectively, the harmonic components of the reactive volt-amperes will be recorded in the ratio $\dfrac{1}{n+\dfrac{1}{n}}$ to their proper value where $n$ is the order of the harmonic, *i.e.*, they will be greatly underrecorded. If, however, the 45 deg relation is made to hold at double normal frequency or at triple frequency, the harmonics will be recorded in ratio to correct values as follows:

| Harmonic | 1 | 3 | 5 | 7 | 9 | 11 | 13 |
|---|---|---|---|---|---|---|---|
| 45° adjustment at double frequency | 1 | 1.13 | 0.86 | 0.66 | 0.53 | 0.44 | 0.33 |
| 45° adjustment at triple frequency | 1 | 2.50 | 1.47 | 1.21 | 1.00 | 0.85 | 0.73 |

If low frequency harmonics are prominent, the double frequency adjustment may well be chosen. If harmonics of consequence in the range 7th to 13th are present, the triple frequency adjustment should be considered. Circuit arrangements just discussed involve losses in the meter much higher than those in the ordinary forms of induction meter, yet there are probably conditions where they would be advantageous.

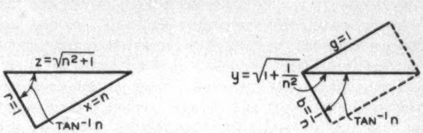

Fig. 2—Impedance of Potential Circuit (Left) and Admittance of Current Circuit (Right) of the Meter of Fig. 1, at Frequency *nN* Relative to Values at Frequency *N*

At frequency *nN*

$$\text{Current in potential circuit} = k_1 \frac{E}{\sqrt{n^2+1}}$$

$$\text{Current in current circuit} = k_2 \frac{1}{n} \cdot \frac{I}{\sqrt{1+\frac{1}{n^2}}}$$

$$\text{Product} = kEI \frac{1}{\sqrt{n^2+1}} \cdot \frac{1}{\sqrt{n^2+1}} = kEI \frac{1}{n^2+1}$$

$$= kEI \cdot \frac{1}{n} \cdot \frac{1}{n+\frac{1}{n}}$$

The general absence of important harmonics in the voltage waves of commercial circuits, the approximate balance of their voltages, and the very great convenience of making use of regularly listed types of meters dictates the choice of regular watthour meters to be connected in circuit with suitable transformers for cross-phase connection for securing 90-deg phase displacement, as the most practical means of measuring reactive kva except in exceptional circumstances.

In the measurement of energy in a three-phase or analogous circuits using double-element meters, when the power factor is low, we encounter the condition of two relatively large torques opposing each other in the meter so that the balance between meter elements becomes of great importance. Similarly, in reactive measurement when the power factor is high, balance of elements is of primary importance. Three-element meters do not suffer from such limitations.

A form of measurement in which a composite quantity is secured, namely, $a \times$ watts $+ b \times$ reactive volt-amperes can be effected by exciting the potential circuit of a wattmeter at a phase intermediate between that of the voltage and 90 deg therefrom. The phase once chosen and established by the proportion of resistance to reactance in the potential circuit, or otherwise, fixes the ratio of $a$ to $b$. The readings of the instrument are then $a \times$ watts $+ b \times$ reactive volt-amperes, and this remains true irrespective of the power factor. Meters, similar to watthour meters, in which this quantity is integrated with respect to time have found considerable use on this continent.

Analysis of alternating-current phenomena is almost wholly built upon the ideas that a fairly equivalent representation of what occurs can be had by considering current, voltage, and power as simple sinusoidal quantities with reference to time and that average rms values of these quantities are almost fundamental entities, at least in ordinary technical discussions. These ideas have lead to the conceptions of "apparent power," "reactive voltamperes," and "power factor," all of which, but especially the last, have so enmeshed themselves in general and specific discussions of technical and practical alternating current problems that, at least in the author's opinion, the true significance of some of these more or less unreal quantities has become obscured; conceptions of reality have been built up around them that are the result of a free and easy use of terms that suggest and help to evaluate but very indirectly indicate what occurs. It is even possible that this has gone so far that fundamentally incorrect ideas actually are distorting technical understanding and diverting effort into wrong channels. The author has the impression that reactive volt-amperage generally is regarded as a measure of the surging of energy in an alternating current circuit. The relation to the latter will be discussed further.

The flow of power in an electric circuit may present itself in various ways depending on the character of the circuit. The flow may be continuously in one direction and at a constant rate as in a steadily loaded d-c circuit; it may be continuously in one direction but pulsating as in the case of a circuit having a non-uniform, unidirectional voltage of any form provided there is no storage of energy; it may have a constant average value when averaged over a sufficient interval of time as in the case of a steady alternating current; or it may be entirely irregular.

Whenever the circuit contains inductance or capacitance, with every change of current or voltage there is a change in the amount of energy stored in the system so that superposed on a more or less steady principal flow of energy there may be a surging of energy due to the increase and decrease of magnetic and of electric energy in the system. When the change of voltage is definitely periodic, this surging can be signalized as reactive volt-amperes and reactive volt-ampere-hours.

With zero time chosen at random and with no other knowledge of the circuit than that given by the measuring devices at the supply end, there can be no distinction between energy stored in the circuit and energy transferred outside except when the voltage is definitely periodic. For example, at the supply end of a d-c circuit, no distinction can be made between energy used to build up a magnetic field and energy consumed in the same interval to supply $I^2R$ losses.

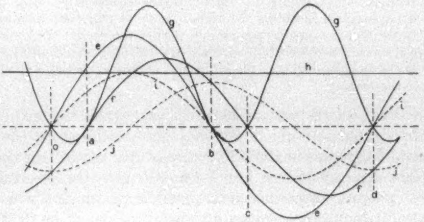

FIG. 3—SINE-WAVE VOLTAGE, CURRENT, AND POWER CURVES WITH CURRENT LAGGING 40 DEG BEHIND THE VOLTAGE

*a-b-c-d* represents times of power reversal

$a$ corresponds to $\frac{\varphi}{\omega}$ in equation (13)

$b$ corresponds to $\frac{1}{2N}$ in equation (13)

| | | | |
|---|---|---|---|
| *e-e* | voltage wave | *h* | average power |
| *f-f* | current wave | *i-i* | active component of current |
| *g-g* | power wave | *j-j* | reactive component of current |

In a single-phase a-c circuit or in each conductor of a polyphase a-c circuit, whenever there is storage of energy, the pulsation of power includes the reversal of the direction of flow of energy. This is a phenomenon that lends itself to exact and simple definition, for the quantities involved are the simultaneously occurring elements of current and voltage. No special interpretation of the significance of harmonic inclusions is required, for no assumption in regard to the type of periodicity need be made.

If we rewrite equation (7) in the form

$$p = \frac{E_m I_m}{2} \cos \varphi \, (1 - \cos 2\omega t) + \frac{E_m I_m}{2} \sin \varphi \sin 2\omega t \tag{10}$$

we observe that that portion of the power of which the coefficient is $(E_m I_m/2)\sin\varphi$ can have negative as well as positive values. The last term is positive during each alternate one-fourth cycle and negative during the other one-fourth cycles. However, taken by itself, this term gives no idea of the positive and negative flow of energy in the circuit except for the two limiting conditions, when $\varphi$ is either 0 or $\pi/2$. At intermediate values, the pulsation of positive power must be considered if we would evaluate separately the positive and negative flow of energy.

At this point will be introduced a quotation from U.S. Patent No. 1,657,262 to Karapetoff, for which the application was filed Oct. 5, 1923:

> "It is the primary object of my invention to provide a metering scheme for low power factor loads which will be more readily understood by the average consumer and is based upon the assumption that any consumer whose installation causes out-of-phase current in the line is, in fact, a periodic borrower of electric energy. During a part of the cycle he takes more energy than he needs, stores the excess in various magnetic fluxes in his apparatus, assuming the current to be lagging, and then returns it to the line during another part of the cycle. He is like a restaurant keeper who buys, say, one hundred pounds of meat in the morning and asks the butcher to take back twenty pounds in the evening."

In the early part of 1931, or just earlier, the author had tabulated much material corresponding to that which appears in the latter part of this paper. In the late summer of that year he had in view the securing of patents on certain instrument arrangements when the patent just mentioned (which was issued in 1928) was brought to his attention; thereupon further work on a proposed paper was discontinued. To round out this general discussion, the following observations seem to be in order.

If an electrodynamic wattmeter is connected to an a-c circuit with a half wave rectifier in series with its potential circuit, another in series with its current circuit, and a third connected in reverse polarity around the current circuit of the instrument to insure continuity in the circuit as a whole, torque will be developed in the instrument only during those periods in which current flows simultaneously in both of the instrument windings. Four situations are possibly to only one of which the instrument so connected will respond. A condition corresponding to each situation will occur at least once in every cycle as follows:

| | Voltage | Current | Power |
|---|---|---|---|
| 1. | + | + | + |
| 2. | + | − | − |
| 3. | − | − | + |
| 4. | − | + | − |

If now, four electrodynamic instrument elements are connected in the single phase a-c circuit through rectifiers as just indicated, each of the four power quantities may be measured separately. If the voltage and current waves are symmetrical, no interest would attach to a separation of (**1**) and (**3**), or (**2**) and (**4**), so (**1**) and (**3**) may be combined as a two-element electrodynamic instrument and similarly (**2**) and (**4**). Furthermore, with symmetrical waves, the energy flow corresponding to (**1**) would equal the energy flow corresponding to (**3**) so a single element could suffice for measuring positive flow and a single element for measuring negative flow; that is, by multiplying by two the reading of one element, and discarding the other.

Moreover, the algebraic sum of the indications of the four elements averaged over an integral number of half cycles would give the same quantity as the reading of an ordinary indicating wattmeter, *i.e.*, the arithmetical difference between the positive and negative flow, so an indicating wattmeter connected in the ordinary manner supplemented by another instrument connected to indicate as per (**2**) or (**4**) would give all the information necessary to evaluate average positive power, average power, and average negative power. Reactive volt-amperes, volt-amperes, and power factor could be calculated from these readings if the power factor is constant and if the flow is sinusoidal. If the wave forms are complex, a self-defining relation between positive and negative flow of energy results.

The distribution of energy flow in the several divisions can be obtained by integrating the power equation with respect to time between limits determined by the epochs corresponding to the reversals of voltage and current. This will be illustrated in its relation to sinusoidal waves.

$$p = EI\cos\varphi - EI\cos\varphi\cos 2\omega t - EI\sin\varphi\sin 2\omega t \qquad (\mathbf{11})$$

$$W = \int p\,dt = EI\cos\varphi\cdot t - \frac{1}{2\omega}EI\cos\varphi\sin 2\omega t + \frac{1}{2\omega}EI\sin\varphi\cos 2\,\omega t \qquad (\mathbf{12})$$

$$W_1 = [W]_{\frac{\varphi}{\omega}}^{\frac{1}{2N}} = \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi - \frac{1}{2\omega}EI\cos\varphi\sin 2\pi + \frac{1}{2\omega}EI\cos\varphi\sin 2\varphi + \frac{1}{2\omega}EI\sin\varphi\cos 2\pi - \frac{1}{2\omega}EI\sin\varphi\cos 2\varphi \qquad (\mathbf{13})$$

$$= \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi + \frac{1}{2\omega}EI\sin\varphi + \frac{1}{2\omega}EI\sin\varphi \qquad (\mathbf{13a})$$

$$= \frac{1}{2N}EI\cos\varphi - \frac{\varphi}{\omega}EI\cos\varphi + \frac{1}{\omega}EI\sin\varphi \qquad (\mathbf{13b})$$

$$W_1 + W_3 = \frac{1}{N} EI\cos\varphi - \frac{2\varphi}{\omega} EI\cos\varphi + \frac{2}{\omega} EI\sin\varphi \quad (14)$$

$$\frac{W_1 + W_3}{\dfrac{1}{N}} = EI\cos\varphi - \frac{\varphi}{\pi} EI\cos\varphi + \frac{1}{\pi} EI\sin\varphi \quad (15)$$

$$= EI\left[\cos\varphi + \frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)\right] \quad (15a)$$

$$W_2 = [W]_0^{\frac{\varphi}{\omega}} = \frac{\varphi}{\omega} EI\cos\varphi - \frac{1}{2\omega} EI\cos\varphi\sin 2\varphi + \frac{1}{2\omega} EI\sin\varphi\cos 2\varphi - \frac{1}{2\omega} EI\sin\varphi$$

$$= \frac{\varphi}{\omega} EI\cos\varphi - \frac{1}{2\omega} EI\sin\varphi - \frac{1}{2\omega} EI\sin\varphi \quad (16)$$

$$\frac{W_2 + W_4}{\dfrac{1}{N}} = \frac{\varphi}{\pi} EI\cos\varphi - \frac{1}{\pi} EI\sin\varphi$$

$$= EI \cdot \frac{1}{\pi}(\varphi\cos\varphi - \sin\varphi) \quad (17)$$

$$\text{Average power} = \frac{W_1 + W_2 + W_3 + W_4}{\dfrac{1}{N}} = EI\cos\varphi \quad (18)$$

$$\frac{\text{Average negative power}}{\text{Average positive power}} = \frac{\varphi\cos\varphi - \sin\varphi}{\pi\cos\varphi - \varphi\cos\varphi + \sin\varphi} = \frac{\varphi - \tan\varphi}{\pi - \varphi + \tan\varphi} \quad (19)$$

Average positive power = average power − average negative power

Reactive volt-amperes $= EI\sin\varphi$

$$\text{Average negative power} = \frac{1}{\pi} EI(\varphi\cos\varphi - \sin\varphi)$$

$$= \frac{\varphi}{\pi}\text{ average power} - \frac{1}{\pi}\text{ reactive volt-amperes}$$

$$= \frac{1}{\pi}(\varphi\text{ average power} - \text{reactive volt-amperes})$$

$$\text{Average positive power} = \left(1 - \frac{\varphi}{\pi}\right)\text{ average power} + \frac{1}{\pi}\text{ reactive volt-amperes}$$

$$= \frac{1}{\pi}[(\pi - \varphi)\text{ average power} + \text{reactive volt-amperes}]$$

TABLE I

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| $\varphi$ | $\sin\varphi$ | $\cos\varphi$ | $\varphi\cos\varphi$ | $\sin\varphi - \varphi\cos\varphi$ | $\frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)$ | $\cos\varphi + \frac{1}{\pi}(\sin\varphi - \varphi\cos\varphi)$ |
| 0° | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 | 1.000 |
| 10° | 0.174 | 0.985 | 0.172 | 0.002 | 0.0007 | 0.986 |
| 20° | 0.342 | 0.940 | 0.328 | 0.014 | 0.0043 | 0.944 |
| 30° | 0.500 | 0.866 | 0.453 | 0.047 | 0.0150 | 0.881 |
| 40° | 0.643 | 0.766 | 0.535 | 0.108 | 0.0347 | 0.801 |
| 50° | 0.766 | 0.643 | 0.561 | 0.205 | 0.0653 | 0.708 |
| 60° | 0.866 | 0.500 | 0.524 | 0.342 | 0.109 | 0.609 |
| 70° | 0.940 | 0.342 | 0.418 | 0.522 | 0.167 | 0.509 |
| 80° | 0.985 | 0.174 | 0.243 | 0.742 | 0.237 | 0.411 |
| 90° | 1.000 | 0.000 | 0.000 | 1.000 | 0.318 | 0.318 |

Column 2 gives reactive factor. Column 3 gives power factor.
Column 6 gives ratio of average negative power to volt-amperes.
Colmun 7 gives ratio of average positive power to volt-amperes.

Table I gives a good idea of the relative magnitudes of the quantities under discussion. It is suggested that average positive power (column 7) could very well form the basis for rate schedules. It would introduce substantially no penalty for power factor for values of the latter above 90 per cent, only slight penalty at 80 per cent, about 22 per cent at 50 per cent power factor and at zero power factor the rate would be based on a quantity just under one-third of the volt-amperes. At 60-deg phase displacement, for each 100 units of net power consumed, 122 units are delivered and 22 returned, yet the reactive volt-amperes are 173, the volt-amperes 200.

Average positive power may be measured directly or by the arithmetic addition of average negative power to average power. If evaluated by the latter method, comparatively rough measurements of the negative contribution would suffice unless the power factor is habitually low; especially is this statement true if the power factor is generally fairly high. Similar statements may be made in regard to average positive energy flow, average energy flow and average negative energy flow. Whatever the character of unbalance or of wave form the measurement procedure just outlined leads to measurable quantities of an unambiguous nature that seem well suited to commercial use. Negative power in its relations to positive power and average power represents a direct comparison of the actual activities in the circuit.

By contrast, reactive volt-amperes is the measure of a quantity that does not appear in the circuit as such but is only the coefficient of an arbitrarily chosen component of power pulsation and has dimensions and magnitude such that the equation $W^2 + S^2 = E^2I^2$ is satisfied. ($S$ = reactive volt-amperes. For complex waves $\Sigma\,[W_1^2 + W_3^2 + \ldots + S_1^2 + S_3^2 + \ldots] \overset{=}{<} E^2I^2$). It is a sort of complementary quantity useful in calculation. It connotes the defect that exists between actual and ideal utilization of the quantities of current and voltage appearing in the circuit.

In what has been said, there is no intention to disparage the use of reactive volt-ampere measurements as a means of determining kilovolt-amperes in the measurement of demand. This last quantity (kva) undoubtedly has its field of usefulness.

## CONCLUSIONS

1. Reactive volt-amperes are not to be identified with the coefficient of the sine term in the equation for instantaneous power.
2. Reactive volt-amperes is an assumed quantity, not a naturally occurring quantity.
3. It is related to average power through the product of the rms values of current and voltage.
4. Certain quantities having to do with the surging of real power have properties that commend further consideration from the viewpoint of commercial application.
5. When the current and voltage waves are purely sinusoidal, the quantities referred to in 4 have easily stated, though somewhat complicated, relationships to the more familiar quantities reactive volt-amperes, power factor, and reactive factor. When the wave forms are complex the relationships are very much involved.

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## Appendix I

It is interesting to examine the power equation in a more general form.

$$e = E_{m1}\sin(\omega t - \varphi_1) + E_{m3}\sin(3\omega t - \varphi_3) + E_{m5}\sin(5\omega t - \varphi_5) + \ldots \qquad (20)$$

$$i = I_{m1}\sin(\omega t - \theta_1) + I_{m3}\sin(3\omega t - \theta_3) + I_{m5}\sin(5\omega t - \theta_5) + \ldots \qquad (21)$$

$$\begin{aligned} p = ei = {} & E_{m1}I_{m1}\sin(\omega t - \varphi_1)\sin(\omega t - \theta_1) \\ & + E_{m1}I_{m3}\sin(\omega t - \varphi_1)\sin(3\omega t - \theta_3) \qquad (22) \\ & + E_{m1}I_{m5}\sin(\omega t - \varphi_1)\sin(5\omega t - \theta_5) + \ldots \\ & + E_{m3}I_{m1}\sin(3\omega t - \varphi_3)\sin(\omega t - \theta_1) \\ & + E_{m3}I_{m3}\sin(3\omega t - \varphi_3)\sin(3\omega t - \theta_3) + \ldots \\ & + E_{m5}I_{m1}\sin(5\omega t - \varphi_5)\sin(\omega t - \theta_1) \\ & + E_{m5}I_{m3}\sin(5\omega t - \varphi_5)\sin(3\omega t - \theta_3) \\ & + E_{m5}I_{m5}\sin(5\omega t - \varphi_5)\sin(5\omega t - \theta_5) + \ldots \end{aligned}$$

$$\begin{aligned} = {} & \frac{E_{m1}I_{m1}}{2}[\cos(\varphi_1 - \theta_1) - \cos(\varphi_1 + \theta_1)\cos 2\omega t \\ & -\sin(\varphi_1 + \theta_1)\sin 2\omega t] + \frac{E_{m1}I_{m3}}{2}[\cos(\varphi_1 - \theta_3)\cos 2\omega t \\ & - \sin(\varphi_1 - \theta_3)\sin 2\omega t - \cos(\varphi_1 + \theta_3)\cos 4\omega t \\ & \quad - \sin(\varphi_1 + \theta_3)\sin 4\omega t] + \ldots \\ & + \frac{E_{m3}I_{m1}}{2}[\cos(\varphi_3 - \theta_1)\cos 2\omega t \\ & \quad + \sin(\varphi_3 - \theta_1)\sin 2\omega t - \cos(\varphi_3 + \theta_1)\cos 4\omega t \\ & \quad - \sin(\varphi_3 + \theta_1)\sin 4\omega t] \\ & \quad + \frac{E_{m3}I_{m3}}{2}[\cos(\varphi_3 - \theta_3) - \cos(\varphi_3 + \theta_3)\cos 6\omega t \\ & \quad - \sin(\varphi_3 + \theta_3)\sin 6\omega t] + \ldots \\ & \quad + \frac{E_{m5}I_{m1}}{2}[\cos(\varphi_5 - \theta_1)\cos 4\omega t \\ & + \sin(\varphi_5 - \theta_1)\sin 4\omega t - \cos(\varphi_5 + \theta_1)\cos 6\omega t \\ & \quad - \sin(\varphi_5 + \theta_1)\sin 6\omega t] \\ & + \frac{E_{m5}I_{m3}}{2}[\cos(\varphi_5 - \theta_3)\cos 2\omega t + \sin(\varphi_5 - \theta_3)\sin 2\omega t \\ & \quad - \cos(\varphi_5 + \theta_3)\cos 8\omega t \\ & - \sin(\varphi_5 + \theta_3)\sin 8\omega t] + \frac{E_{m5}I_{m5}}{2}[\cos(\varphi_5 - \theta_5) \\ & \quad - \cos(\varphi_5 + \theta_5)\cos 10\omega t \\ & - \sin(\varphi_5 + \theta_5)\sin 10\omega t] + \ldots \qquad (22a) \\ & + \ldots \\ & + \ldots \end{aligned}$$

$$\begin{aligned} P = {} & \frac{E_{m1}I_{m1}}{2}\cos(\varphi_1 - \theta_1) + \frac{E_{m3}I_{m3}}{2}\cos(\varphi_3 - \theta_3) \\ & + \frac{E_{m5}I_{m5}}{2}\cos(\varphi_5 - \theta_5) + \ldots \qquad (23) \end{aligned}$$

It may be observed that but few terms are involved in the evaluation of average power, but in the pulsation and storage of energy, products involving the fundamental and a large harmonic are of much more importance than those terms involving that harmonic alone.

With a purely resistance load, the resistance remaining constant through the cycle

$$\frac{E_1}{I_1} = \frac{E_3}{I_3} = \frac{E_5}{I_5} = \text{etc.}$$

In this case, many pairs of terms could be combined since $E_1I_3 = E_3I_1$, etc.

## Appendix II

### SIGN FOR REACTIVE VOLT-AMPERES

The proper sign of reactive volt-amperes caused by the presence of inductance in a circuit should emerge of itself from a consideration of the previously adopted conventions for fundamental quantities. These are:

1. The algebraic conventions for complex quantities and direction of rotation of time vectors.
2. Definition of impedance as

$$Z = R + jX$$

where $X$ is positive for an inductive reactance.

From these two it follows that admittance $Y$ is

$$Y = \frac{R}{Z^2} - j\frac{X}{Z^2}$$

Then power $P$ may be expressed either as

$$P = E^2Y = E^2\frac{R}{Z^2} - jE^2\frac{X}{Z^2}$$

or

$$P = I^2Z = I^2R + jI^2X$$

depending upon whether the voltage $E$ or the current $I$ is used as the original reference axis. Thus the sign of inductive reactive volt-amperes correctly may have either a negative or a positive sign but, to avoid confusion, one sign should be established arbitrarily.

The reasons which have led to the practice of plotting inductive reactive volt-amperes with a negative sign may be summarized as follows:

1. Counter-clockwise has been established as the positive direction of rotation for voltage, current, and other vector diagrams.
2. The great preponderance of multiple distribution involves a prevailing preference for a voltage reference vector (in voltage-current diagrams).
3. Since powers and reactive volt-amperes at equal voltages are proportional to the corresponding currents, it is desirable to have the corresponding diagrams recognizably similar, and the corresponding complex numbers with similar signs.
4. With counter-clockwise rotation and a voltage reference vector adopted, consistency requires that leading quantities be represented as counter-clockwise and lagging quantities as clockwise relative to the reference vector.
5. In all cases in which convenience dictates alternatives to the above arbitrary convention as, for example, a current reference vector, this may freely be done by clearly specifying the conventions substituted.
6. While theoretical reasons have been proposed to show why either one or the other of these conventions can logically be used, when these are examined carefully it does not appear that the argument on this basis can be made conclusive for either convention.

Articles appearing in contemporary literature show a surprising difference in point of view from which the sign of inductive reactive power may be determined and about an equal division between those favoring a negative sign and those opposed to it. However, it is recognized by all that an arbitrary convention is desirable and, since one convention may be applied as easily as the other mathematically, that one should be chosen which clearly is more advantageous from a practical standpoint.

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## Discussion

### REACTIVE POWER CONCEPTS IN NEED OF CLARIFICATION

(KNOWLTON)

### REACTIVE AND FICTITIOUS POWER

(SMITH)

### POWER, REACTIVE VOLT-AMPERES POWER FACTOR

(FORTESCUE)

### OPERATING ASPECTS OF REACTIVE POWER

(JOHNSON)

### REACTIVE POWER AND POWER FACTOR

(LYON)

### NOTES ON THE MEASUREMENT OF REACTIVE VOLT-AMPERES

(PRATT)

**L. A. Doggett:** The writer makes the following recommendations:

1. Considering the typical modern system, we agree on the assumption that there is but one type of reactive power, that associated with the storage and discharge of magnetic energy. On that basis a survey of the active and reactive power in the various parts of a system would yield a record somewhat as follows:

| | Survey | | | |
|---|---|---|---|---|
| | Receiving | | Supplying | |
| Part | Active power $I^2R$ | Reactive power $I^2X$ | Active power $I^2R$ | Reactive power $I^2X$ |
| .. | .. | .. | .. | .. |
| .. | .. | .. | .. | .. |

A synchronous motor either may receive or supply reactive power, thus defined. A static condenser always supplies reactive power. This recommendation is in agreement with the suggestions of Mr. J. A. Johnson.

2. As to the sign to be attached to reactive power of the magnetic type: consistency with the convention of counterclockwise rotation of vectors and with the conventions of polar coordinate analytical geometry calls for the *negative* sign in front of $jQ$, when $jQ$ represents reactive power of the magnetic type. This is

developed at length on pages 29-31 of the writer's "A-C Analysis by the $I^2R - I^2X - I^2Z$ Method." (Edwards Brothers, Inc., Ann Arbor, Michigan, 1933.)

3. Recommend for all cases, sinusoidal or otherwise that $\Sigma E_n I_n \sin \theta_n$ be made the standard definition for reactive power for both single phase and polyphase cases.

4. Recommend that in all cases the apparent power be defined as

$$\sqrt{\overline{\Sigma E_n I_n \cos \theta_n}^2 + \overline{\Sigma E_n I_n \sin \theta_n}^2}$$

which is not always the same as the product of the voltmeter and ammeter readings.

5. Recommend that power factor be defined as

$$\frac{\Sigma E_n I_n \cos \theta_n}{\text{apparent power}}$$

where apparent power is as defined in (**4**).

Note: These definitions obviate the necessity of the terms "fictitious power," "deforming power," and "distortion power."

On the basis of the foregoing definitions the writer has worked out a fairly complete analysis of a wide range of alternating current problems; also a great deal of experimental work with nonsinusoidal cases, all of which have led to the adoption of these definitions. They have been incorporated in the booklet in the foregoing reference. The validity of the law of conservation of reactive power as well as the law of the conservation of active power has become so well established in the writer's mind that it is applied here tentatively to the study of the mercury arc rectifier, with the results indicated in the following table.

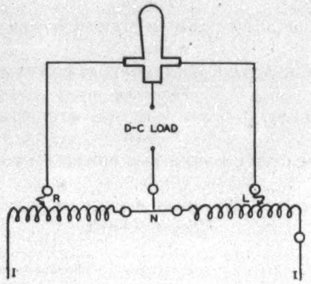


FIG. 1

TABLE I

| Item | $I^2R$ | $I^2X$ |
|---|---|---|
| (1)...Input | 891.2 | 157.5 |
| (2)...Output | 606.0 | |
| (3)...Arc | 180.0 | |
| (4)...Transformer | | |
| *RN* | 44.2 | 28.0 |
| *LN* | 35.6 | 28.0 |
| (5)...Transformer | | |
| *RI* | 20.3 | 28.0 |
| *LI* | 20.3 | 28.0 |
| (6)...Core loss | 3.0 | |
| Excitation | | 4.0 |
| (7)...Output + losses | 909.4 | 116.0* |

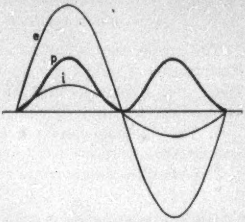
(1) By wave analysis up to and including the 7th harmonic.
$\Sigma I^2R = \Sigma (P_1 + P_3 + P_5 + P_7)$, also by wattmeter.
$\Sigma I^2X = \Sigma (Q_1 + Q_3 + Q_5 + Q_7)$.
(2) From oscillograms.
(3) From oscillograms, vacuum tube voltmeter, and wattmeter.
(4) $I^2X$ from $d/dt$ of $(\frac{1}{2}LI^2)$, where $L$ = the inductance of *RN*, *LN*.
(5) $I^2$ from oscillograms.

*Approximation in assuming $L$ constant for all types of current values and shapes.

These results were obtained by Mr. R. B. Tomlinson in connection with a Master's Degree thesis at the Pennsylvania State College. Oscillograms of all voltages and currents were taken. Fig. 1 shows the location of the oscillograph current vibrators; the letters apply to Table I.

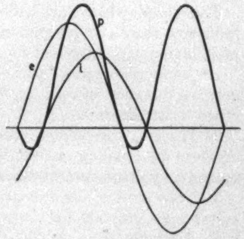
To sum up, the writer believes from experience that reactive power follows a law similar to the law for the conservation of energy. Professor C. D. Busila says that reactive power is not conserved in exchanges between circuits of different frequency, for example, between the rotor and the stator of the induction motor. With this statement the writer is not in agreement. This opinion is based on the erroneous assumption that the reactances of stator and rotor are separate entities. As a matter of fact, as brought out in Still's "Elements of Electrical Machine Design," 1932 Edition, pages 473-478, the reactance of an induction motor is 95 per cent or more associated with the stator. In the past it has been customary for convenience in transformer treatments of induction motors to split the reactance equally between stator and rotor.

FIG. 2—INSTANTANEOUS VALUES OF VOLTS, AMPERES, AND POWER FOR A PHASE ANGLE OF ZERO DEGREES BETWEEN VOLTAGE AND CURRENT. AVERAGE VALUE OF POWER IS $E_mI_m/2$. INSTANTANEOUS POWER IS PROPORTIONAL TO INSTANTANEOUS PHASE-TORQUE



**Frank W. Godsey, Jr.:** The half-formed idea in the minds of some operators that reactive power is a fictitious quantity representing a mathematical convenience is in error. Harmonic power fluctuations in single-phase circuits are increased with increases in phase displacement between current and voltage. With a fixed load, the demand upon flywheel and governor of the prime mover rises with increases in phase angle in order to maintain stability of operation. Maximum mechanical forces on windings, supports, and insulation rise; and supersynchronous torque variations in shafts and couplings increase, resulting in changes in load on bearings and fittings. (See Figs. 2 and 3.)

FIG. 3—INSTANTANEOUS VALUES OF VOLTS, AMPERES, AND POWER FOR A PHASE ANGLE OF 45 DEGREES BETWEEN VOLTAGE AND CURRENT. AVERAGE VALUE OF POWER IS $E_mI_m/2.828$. INSTANTANEOUS POWER IS PROPORTIONAL TO INSTANTANEOUS PHASE-TORQUE



Assuming a superposition principle and obtaining total voltamperes through a summation of the products of individual frequency components of the voltage multiplied by their respective current components, a true power factor as at present defined would be obtained by dividing power by total voltamperes. However, the only readily available measuring instruments give true power, effective volts, and effective amperes. Where only the current for instance, has harmonics as in a non-linear resistance load, the power factor may be unity. And yet as calculated from power factor = $P/EI$, the result always will be less than unity. Therefore, the old conception of power factor is too ponderous to use except in the special case of sine wave voltage and current.

It has been suggested that a distortion factor be applied in current, voltage, and power factor measurements to make possible a reconciliation with reactive power measurements. This again is a subterfuge that is applicable only in a specific case and under fixed conditions. A distortion factor is an added complication to an already confused situation.

Reactive power in single-phase circuits is readily measured with meters ordinarily available, and since the voltage waves in most circuits are very close to sine waves, the measured reactive power will not include any terms due to current harmonics as these will cancel out over a complete cycle. Therefore, the writer suggests that the term reactive power in single-phase circuits refer only to the fundamental frequency component of the reactive power, and that when both current and voltage waves have harmonics that the total reactive power component be called the total reactive power.

It appears that most of the difficulty in evaluating power factor lies in the attempt to carry over into the non-sinusoidal circuit the convenient relations existing in the special case of sinusoidal voltage and current waves. Since there can be no reconciliation between reactive power, true power, and power factor except in special cases, the obvious remedy is to abandon any attempt to make such a reconciliation.

Station operators dispatch real power and reactive power over a system, not power factor. The power salesman is very much interested in power factor because of the larger investment in operating plant required for low power factor loads and increased operating losses incidental to that condition; therefore power rates should be and are higher for low power factor loads. The user of power is interested in power factor for the same reasons as the power salesman, and has an incentive to watch load characteristics in order to take advantage of a lower rate.

Therefore, it appears that the only individuals interested in power factor calculations are the men who adjust power rates. Why not then, as referred to in Mr. Knowlton's review of the subject, banish power factor from the academic circle and change its definition in such a way that it fulfills all of the requirements of the rate adjusters without attempting to serve a post on the technical and operating staff? Reactive power and real power fill all the requirements of the mathematician and operator, and Fourier series describes non-sinusoidal voltages and currents accurately.

A reasonable solution would be to multiply the effective value of current by the effective value of voltage to obtain the maximum demand for plant investment. Dividing the real power measured in the circuit by this product would give a power factor = $P/E_{eff} \mathrm{x} I_{eff}$, which is a real measure of the customer's utilization of the operating plant demanded by his load. It has no significance with respect to reactive power except in special cases, and is not intended for any use except the evaluation of the utilization efficiency of a power consumer with respect to the operating plant required to supply the load. It is independent of "distortion factors" and reactive power measurements, but it is accurate in evaluating required plant investment and operating losses.

Going now to the case of polyphase systems, we find that for the balanced system with sine wave voltages and currents, the same conditions apply as in the single-phase case. Again, the writer suggests that reactive power refer only to the fundamental frequency component of the out-of-phase power; this is the value usually measured by rkva meters since voltage waves seldom have large harmonics. Let the entire out-of-phase component be known as the total reactive power as in the single-phase case; if a further description of a particular case is necessary, oscillograms must furnish it in almost every instance.

In calculating average power factor for a polyphase system, effective phase voltages should be multiplied by effective phase currents of the same frequency and the products added to obtain total kilovoltampere required of the generating plant. Dividing the total measured power by this sum gives power factor, which has no mathematical significance, but accurately expresses the plant utilization efficiency of the load and is a measure of line losses. In most industrial loads the voltage supplied by the power company is close enough to a sine wave that through the geometry of the circuit phase voltages are known after a few simple calculations.

The problem of metering such circuits is relatively simple since effective values of current and voltage are to be measured. Efficient thermo-couple instruments are available which will give correct results, and rectifier type meters may be used in the majority of cases to measure kilovoltampere without serious error. In the average polyphase system, it is sufficient to totalize all effective currents either in a thermal element, rectifier outputs, or some similar method, and the potential coil of the kilovoltampere meter is supplied through a rectifier in a suitable voltage phase to measure kilovoltampere.

Suggested changes are tabulated as follows:

### SINGLE PHASE

Reactive power—Fundamental frequency component of the out-of-phase power component.

Total reactive power—Total out-of-phase power component including the fundamental.

Power factor—Power divided by the product of effective volts by effective amperes, with no relation to reactive power except in special cases.

### POLYPHASE

Reactive power—Sum of fundamental frequency components of out-of-phase power components for all phases.

Total reactive power—Sum of total out-of-phase power components including the fundamentals for all phases.

Power factor—Total power divided by the sum of the individual products for the several phases of effective phase voltages by effective phase currents respectively, with no mathematical significance with respect to reactive power except in special cases.

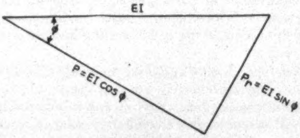


Fig. 4

**V. Karapetoff:** This discussion considers the problem of power factor from a purely practical point of view, namely that of feasible measurements in unbalanced polyphase industrial circuits. Any definition of power factor that cannot be realized with fairly simple practical measuring instruments will remain a dead letter; on the other hand, a definition that may not be quite rigorous theoretically may prove to be of great practical usefulness if the corresponding measurements are simple and can readily be understood by the average operating engineer.

To illustrate this proposal by a concrete example, consider a large three-phase arc furnace with the currents in the three phases not balanced and containing appreciable higher harmonics. Also assume for the sake of generality that the terminal voltages are somewhat distorted in magnitude and phase and are not quite sinusoidal. The neutral point will be assumed to be not accessible. Let a clause in the contract with the operating company prescribe a graduated penalty for low power factor. The question is to determine the average value of the power factor for a day, a melting cycle, a month, etc.

For a contrast, consider also a simple single-phase laboratory circuit consisting of a constant resistance and constant inductance in series and connected to a strictly sinusoidal source of voltage of constant magnitude and frequency. Let the nature of the circuit apparatus be such that the current also is strictly sinusoidal. The power relations are represented by the familiar triangle in Fig. 4, in which, by a commonly accepted definition, the power factor is equal to the cosine of the angle $\phi$. This triangle may be constructed by performing one of the following 6 sets of measurements:

| | | | |
|---|---|---|---|
| (1) | $E$, $I$, and $P$ | (4) | $\phi$, $E$, and $I$ |
| (2) | $E$, $I$, and $P_r$ | (5) | $\phi$ and $P$ |
| (3) | $P$ and $P_r$ | (6) | $\phi$ and $P_r$ |

In this table $E$ is the effective value of the terminal voltage, as read on a voltmeter, $I$ is the effective value of the current read on an ammeter, and $P$ is the average power read on an indicating wattmeter. $P_r$ is the so-called reactive power, read on the same wattmeter with the current in its potential winding "quadratured," that is, displaced by 90 degrees from its phase when measuring $P$. Reactive-power meters are used in practice, and methods for quadraturing the shunted current are well known. The angle $\phi$ is determined by means of a power-factor meter, of which there are several types on the market. The table simply gives the 6 ways in which the right-angle triangle in Fig. 4 may be constructed, knowing 2 of its parts. Assuming the instruments and the readings to be accurate, the same triangle will be obtained from any of the 6 combinations of data, and the theory involved is well understood by most operating engineers.

An irregular polyphase circuit, such as that of the above-mentioned arc furnace, has no intrinsic or scientific power factor. If for some practical reasons it seems desirable to introduce such a concept, it must largely be a matter of definition and agreement. Of course, the definition must be such that for a balanced sinusoidal $n$-phase circuit this definition will agree with that in Fig. 4, because such a symmetrical circuit may be split into $n$ independent identical single-phase circuits. Moreover, the practical requirement of averaging values over an appreciable interval of time, and sometimes of measuring the maximum demand as well, makes the use of integrating instruments mandatory.

Let us therefore consider again the foregoing table of 6 sets of measurements and ask ourselves which of these could be generalized for use with an arc furnace by means of integrating instruments. It will be seen at once that all the combinations involving $E$, $I$ or $\phi$ are less suitable or desirable, partly because of lack of proper instruments, and partly because we do not know what the "total volt-amperes" might be in such a circuit with higher harmonics and with an inaccessible neutral. This leaves the combination (3), with $P$ and $P_r$ to be measured by watt-hour meters. Measurement of $P$ is standard in practically every installation, leaving only the question of $P_r$ to be considered.

It is proposed for the purposes of defining and computing the value of the power factor on an unbalanced polyphase circuit, even with non-sinusoidal currents and voltages, that the reactive power or energy be defined as the reading of a polyphase wattmeter or watt-hour meter with its potential windings quadratured. By quadraturing in this case is meant providing such connections that the shunt currents actually would be shifted by 90 degrees in phase when the applied phase voltages become balanced. With unbalanced and unsymmetrical voltages the actual shift in phase may be different from 90 degrees. This, however, is foreseen in the above definition, the actual reading of the meter under such conditions being meant, without any change in connections or other compensation. With $P$ and $P_r$ reading directly on two integrating watt-hour meters, the triangle in Fig. 4 becomes determined, thus making it possible to compute the "equivalent" values of the angle $\phi$ and the total volt-amperes $EI$. The simple practical procedure would be to determine $\tan \phi = P_r/P$, and to find the corresponding $\cos \phi$ from trigonometric tables, without constructing the triangle. For various practical methods of quadraturing meters see, for example, the writer's "Experimental Electrical Engineering," Third Edition, Vol. II, pp. 139-143.

The foregoing solution of the problem may be called an asymptotic solution in that the value of the power factor, so determined, asymptotically approaches the recognized scientific value as the polyphase circuit in question becomes more balanced and the currents and the voltages more nearly sinusoidal. The method involves no new instruments or connections and no new theory, and simply is based on an agreement to continue to call the readings of a reactive volt-ampere meter "reactive power," even when the circuit becomes unbalanced and the currents and the voltages contain higher harmonics. Of course, on such circuits types of meters should preferably be used which give fairly accurate values of true power even with appreciable higher harmonics in the currents and the voltages. It is believed that the best meters now on the market satisfy this requirement within reasonable limits.

While offering the foregoing solution of the problem so long as the profession and the industry desire to retain the concept of power factor, even on complicated unbalanced polyphase circuits, for characterizing such circuits and determining energy rates and penalties, the writer believes that such circuits should be characterized by more than one factor. The degree of unbalance for real power, for reactive power, and for phase currents, the various peak demands, distortion of the terminal voltages, higher harmonics in the currents—all of these are separate "misdemeanors" and should be penalized individually. A separate measurement of true and reactive power of positive and negative sequence (four meters with maximum-demand attachments) would be a step in the right direction and would enable the consumer to analyze the conditions in his plant and possibly to improve them. A somewhat different solution for unbalanced circuits, based upon the concept of "circulating power," has been developed by the author and described in the U. S. Patent 1,566,879, of December 22, 1925.

**R. D. Evans:** Several of the papers have discussed the sign to be associated with inductive reactive volt-amperes. The most rational choice, in the writer's opinion, is to associate the sign for the flow of reactive volt-amperes with the sign for the flow of real power, as pointed out by Mr. Johnson in his paper. It generally is accepted that the positive sense of power flow is from the generator to the resistive load; similarly, for reactive volt-amperes the above convention gives for the normal positive flow of inductive reactive volt-amperes from the (over-excited generator) to the inductive load. It is felt that there is a very decided advantage in using the same positive sense of current flow for both power and inductive reactive volt-amperes. From this point of view, the user of electric service may be charged for power at one rate and reactive volt-amperes (inductive) at another rate. If the opposite convention were employed, it would be necessary to charge the user for the inductive reactive volt-amperes which he supplies to the system.

The above convention as to reactive volt-amperes also corresponds to the signs commonly associated with magnetic energy. There also is some use of an expression giving the difference of inductive and capacitance stored energy with the positive sign corresponding to inductive reactive volt-amperes. Another form that this argument takes is that power is equal to $RI^2$ and, therefore, reactive volt-amperes is $XI^2$ and since $R + jX$ is the accepted convention for impedance $(R + jX)I^2$ should represent both dissipative power and reactive volt-amperes. The inverse proposition of representing power as $(G + jB)E^2$ is held to be of no moment because impedance is an accepted convention and admittance is a derived quantity and defined as the reciprocal of impedance in the latest rules of the American Standards Association.

Doctor Fortescue in his paper has employed vectors to represent the *instantaneous* values of total power, dissipative power, and energy flow in reactive elements of the circuit and these quantities, of course, also give *average* values of volt-amperes, power and reactive volt-amperes. He also points out how the instantaneous time variation in these quantities is represented correctly for the series circuit. While the relative time variation of these quantities varies with the type of network under consideration, yet these circuits may be represented, in so far as the power supply is concerned, by means of the equivalent circuit in the series form. In view of the fact that most circuits are of the series form in which the dissipative power reaches its maximum ahead of the instant of maximum stored energy, it is felt that Doctor Fortescue has introduced an additional reason for plotting power diagrams in the form $P + jQ$ for an inductive resistance load circuit.

In favor of the opposite convention, there appears to be essentially only one argument, that of the convenience in associating lagging current and lagging reactive volt-amperes. It is believed that this association is unfortunate as it does not correspond with the physical facts involved in the flow of energy in the simple series circuit involving resistance and inductive reactance. It is suggested that instead of the association of lagging current with lagging reactive volt-amperes, it is preferable to consider the sign of the flow of inductive reactive volt-amperes the same as for the flow of real power, which appears to be a simpler relation than one which seems to be of somewhat more fundamental nature.

**J. J. Smith:** In dealing with the subject of apparent power, Professors Lyon and Smith give a satisfactory definition for the single-phase case where the apparent power becomes the product of the voltage across the circuit and the current in the circuit. It then is shown that the apparent power can be divided into three components which may be identified as real power $P$, reactive power $P_r$, and distortion power $P_d$. This definition of apparent power may readily be extended to the case of a balanced polyphase system by writing it in the form—apparent power $= pE_{\mathrm{N}}I$

where

$E_{\mathrm{N}}$ is the voltage from each line to neutral
$I$ is the current in each line
$p$ is the number of phases

This extension involves recognizing a balanced polyphase circuit as made up of $p$ single-phase circuits.

When the polyphase circuit is unbalanced, a new factor arises, which has to be taken care of. The definition suggested in both of these papers for apparent power (the maximum power obtainable when the phases and wave forms of the currents and voltages are varied in every possible manner consistent with Kirchhoff's law, the effective values remaining constant) suffers from a number of disadvantages. The definition may involve very complicated equations in finding out what the maximum power is; also the solution may require physically impossible circuits. For example, even in the simple-looking case illustrated in Fig. 2 of Professor Lyon's paper it will be found that in order to determine the value of $R$ given in Fig. 2B it is necessary to solve two simultaneous equations in $R$, one of which is of the 4th order and the other of the 8th order; furthermore, one of these resistances comes out negative. Such drawbacks complicate the practical use of the definition.

From the standpoint of application, it therefore seems necessary to have a more practical definition. All commercial circuits primarily are designed to be balanced systems, and thus unbalanced voltages or currents mean that the supply system is not being utilized in the most effective manner. A definite single value can be taken for the voltages since they are fairly well balanced in most cases. In the case of the currents, there does not seem to be a logical reason why, in varying their phase and wave form to find the maximum power, the magnitudes of the currents in the lines should not also be varied, subject to the condition that the current in any line should not exceed the current in the line which is a maximum under the given condition of operation. This leads to a definition of apparent power which is based upon equal effective currents in all the lines and may be stated as follows:

$$\text{Maximum apparent power} = pE_{\mathrm{N}\,max}\,I_{max}$$

where

$p$ is the number of phases
$E_{\mathrm{N}\,max}$ is the maximum rms voltage from any line to neutral, corresponding to the maximum phase-to-phase rms voltage in a balanced system

and

$I_{max}$ is the maximum rms current in any one line.

This definition has the advantage that the quantities involved, namely voltage and current, are directly measurable and the result may immediately be obtained from the product of these quantities. It also cannot give rise to impossible circuits containing negative resistance, etc.

Doctor F. B. Silsbee proposed a similar definition in a paper entitled *Power Factor of Polyphase Systems* presented before the A.I.E.E. in 1920. Unfortunately this particular definition was not included in the abstract published in the TRANSACTIONS of the A.I.E.E., Volume XXXIX, 1920, p. 1465.

**C. C. Herskind:** The definition of power factor is discussed in connection with the ideas advanced in the various papers in this symposium.

Referring to Professor Smith's paper, equation (1) furnishes a sound basis for discussing the single-phase circuit. From this relation we may define the apparent power for a single-phase circuit as the product of volts and amperes. If the quantity $\Sigma E_n I_n \cos\theta_n$ is used to define the real power and the quantity $\Sigma E_n I_n \sin\theta_n$ the reactive power, the remaining term in the equation may be called the harmonic or distortion power. The apparent power in a single-phase circuit may then be expressed by the relation

$$E^2I^2 = P_{ap}^2 = P^2 + P_r^2 + P_d^2$$

Inasmuch as power factor for a single-phase circuit is now defined in the A.I.E.E. Standards by the ratio $\dfrac{P}{P_{ap}}$ and as this ratio includes all the factors which may arise in a single-phase circuit, the writer believes that this definition should be retained instead of adopting the one proposed by Professor Smith, $P/\sqrt{P^2 + P_r^2}$, in definition 5 in his paper. The power factor of a single-phase circuit then is

$$\text{Power factor} = \frac{P}{P_{ap}} = \frac{P}{EI} = \frac{P}{\sqrt{P^2 + P_r^2 + P_d^2}}$$

In order to be consistent with this definition of power factor, reactive factor and harmonic factor may be defined by

$$\frac{P_r}{P_{ap}} \text{ and } \frac{P_d}{P_{ap}}$$

if desired.

In the case of polyphase circuits the present A.I.E.E. definition is unsatisfactory. Reviewing the A.I.E.E. definitions we find that power factor in polyphase circuits is defined as the ratio of total active power to the total vector volt-amperes where the total vector volt-amperes is the square root of the sum of the squares of the total active power and the total reactive power. The total reactive power is defined in turn as the algebraic sum of the reactive powers, $\Sigma E_n I_n \sin\theta_n$, corresponding to the separate harmonic components of the system. This definition does not take into account the effect of the distortion power which is due to the presence of harmonics of non-corresponding frequencies, that is, the definition of the vector volt-amperes considers only the real power and the reactive power. From the analysis of the single-phase circuit we have found that the apparent power is defined by three quantities, namely the real power, reactive power, and distortion power.

In view of the increasing use of vacuum-tube devices in power applications, it is important that the effects of harmonics on any definition of power factor be fully understood. In the past, unbalance power has been a source of trouble in determination of power factor and therefore it should also be covered by the new definition. In order to take these factors into account, it is believed the power factor in a polyphase circuit should be defined as $P/P_{ap}$.

When the polyphase system is balanced, with distortion present, the apparent power may be determined the same as for the single-phase circuit by replacing the polyphase system by its component single-phase circuits.

Difficulties have arisen in the definition and determination of apparent power when the polyphase system is unbalanced. Some of these difficulties have been discussed by Professor J. J. Smith, who has suggested a definition for a maximum apparent power. If this definition for apparent power is accepted, the power factor in the case of unbalanced polyphase circuits will be an overall factor expressing the ratio of the actual loading with unbalanced currents to the maximum balanced load which could be obtained with the same maximum current. The definition of power factor then includes the effects of wave displacement, wave distortion and unbalance; to take these effects into account separately, it may be desirable to make further definitions. The merit of such a definition of apparent power lies in its practical usefulness, whereas other definitions of apparent power at the present time have only an abstract mathematical significance.

**C. H. Sanderson:** Mr. J. A. Johnson's paper presents a clear and logical view of a subject which is far from being clear and logical to the majority of our operators. Their major problem is efficient and safe overall system operation in which load control and voltage control are prominent factors. Early in their experience they learn that the active or useful power circulating in the system has a companion, or an opponent, variously called reactive power or wattless power or useless power. And they come to know that, given the proper facilities, they can so dispatch these two kinds of power as to make some real use of the latter in the proper control of the system.

Naturally, given his own choice, the operator would prefer to consider inductive reactive power as a positive quantity always. It is confusing to him, lacking the mathematical background, to think in minus quantities and to consider the dispatching of minus quantities of power. Moreover the vector representation of these power components as given in other papers of this symposium indicates that plotting of inductive reactive volt-amperes as positive is more natural and logical.

The system of reasoning presented by Mr. Johnson, which may commonly be applied to any portion of the power system under any condition of power flow, and which permits a further simplification of instrument indications and log records will no doubt receive the hearty endorsement of all system operators.

**C. A. Corney:** The adoption of the conventions proposed by Mr. Johnson in his paper would simplify the discussion and handling of reactive power. In the past there has been considerable confusion due to the fact that individuals as well as groups of operating men have built up their own nomenclature and conceptions which were fundamentally sound but differed in the manner in which the terms were applied and to the point of reference. For example, it is essential to know whether "lag" or "lead" is with reference to the bus or to the incoming line. Thus one group would consider reactive power in terms of the effect which it would have on its generators while another would consider purely its academic properties. Thus the parties to a discussion would talk at cross purposes until one or the other became aware that each was using a different basis. Each would be fundamentally correct, but naturally each party would believe its conception was the better and would oppose any change, and the difficulties of handling the flow of reactive power would persist.

In the early days of interconnection in New England, there was a considerable amount of this confusion and talking at cross purposes particularly at the system operators' meetings which contributed to the difficulties of voltage regulation and line loadings.

Within the writer's organization we have tried to clarify discussion by comparing interconnecting lines with over-and under-excited generators, but even here it has been necessary to take time to explain this basis.

It would require some time, of course, to convert our present conceptions over to Mr. Johnson's conventions, but after a short period of use these would become convenient and familiar terms. At least we would all have a common nomenclature for handling reactive power which is an important factor in successful interconnection.

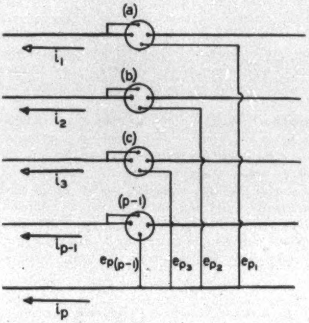


FIG. 5

**Michel G. Malti:** This discussion is concerned with reactive power in polyphase circuits. Consider a $p$-phase circuit and let there be $(p - 1)$ wattmeters connected (Fig. 5) such that the current in wattmeter $(a)$ is $i_1$ and the voltage across it is $e_{p1}$; the current in wattmeter $(b)$ is $i_2$ and the voltage across it is $e_{p2}$ . . . and finally the wattmeter $(p - 1)$ has the current $i_{p-1}$ and the voltage $e_{p(p-1)}$. From the definition of power it may be proved that:

$$P = \frac{1}{T}\int_0^T [e_{p1}i_1 + e_{p2}i_2 + \dots e_{p(p-1)}i_{(p-1)}]\,dt \tag{1}$$

If $p$ wattmeters be connected so that each reads the power per phase either in a star circuit (Fig. 6) or in a mesh circuit (Fig. 7) the equations for power are respectively:

$$P = \frac{1}{T}\int_0^T (e_{01}i_1 + e_{02}i_2 + \dots e_{0p}i_p)\,dt \tag{2}$$

$$P = \frac{1}{T}\int_0^T (e_{12}i_{12} + e_{23}i_{23} + \dots e_{p1}i_{p1})\,dt \tag{3}$$

It may be proved that equations (1), (2), and (3) are identical and that they are most general and apply to any number of phases, any wave form, any condition of balance or unbalance, and any difference in phase between $e$ and $i$. In other words the $(p-1)$ wattmeters connected as shown in Fig. 5 give the total power in a $p$-phase circuit under all conditions. [Editor's Note: For proofs of this see "Measurement of Energy of Polyphase Currents," by A. Blondel, *Proc. International Elec. Congress*, Chicago, Ill., 1893, pp. 112-7 (published by A.I.E.E.) and "Electrical Measurements" (a book), by F. A. Laws, first edition, 1917, McGraw Hill Book Co., p. 1917.]

Now let us use $(p-1)$ wattmeters to measure power (active and reactive) in $p$-phases. Let these wattmeters be connected as shown in Fig. 5. Each wattmeter shall consist of one current element having a resistance shunt and three voltage elements. One voltage element shall consist of a non-inductive resistance $R$, the other of an inductance $L$ so adjusted that, at fundamental frequency, its reactance $X_{L1}$ shall be numerically equal to $R$; and finally the third element shall consist of a capacitance $C$ so varied that its reactance $X_{C1}$, at fundamental frequency, also shall be numerically equal to $R$. These elements shall be so arranged that they can be switched into the circuit independently so that when the voltage coil of the wattmeter is actuated by a current flowing through any one element the other two coils are open. Let the voltages corresponding to $R$, $L$, and $C$ be respectively $e_{p1}, e_{p2}, \ldots e_{p1}', e_{p2}' \ldots$ and $e_{p1}'', e_{p2}'' \ldots$. Then the sum of the power readings when the resistance element is used will be given by equation (2), and the sum of the readings of the inductance and capacitance elements will be respectively:

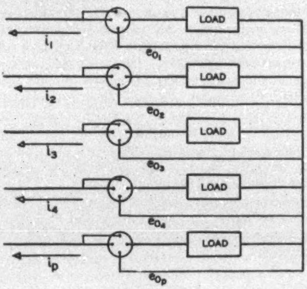


FIG. 6

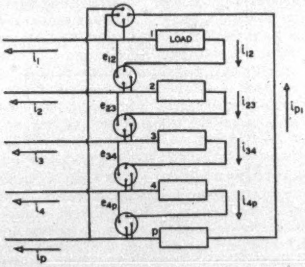


FIG. 7

$$P_r' = \frac{1}{T}\int_0^T (e_{01}'i_1 + e_{02}'i_2 + \ldots e_{03}'i_3)\,dt \qquad (4)$$

$$P_r'' = \frac{1}{T}\int_0^T (e_{01}''i_1 + e_{02}''i_2 + \ldots e_{03}''i_3)\,dt \qquad (5)$$

We shall define the polyphase reactive power as:

$$P_r = \sqrt{-P_r'P_r''} \qquad (6)$$

Now examine the consequences of this definition.

Note that equation (4) corresponds to equation (2). Moreover if $e_{01}, e_{02} \ldots$ are non-sine voltages and if $i_1, i_2, \ldots$ are non-sine currents, then the result of substituting a Fourier series for the voltages and currents in equation (2) is to give the total power in all the phases due to all the harmonics. Thus, upon integration equation (2) becomes:

$$P = \sum_p \sum_n E_n I_n \cos\phi_n \qquad (7)$$

Where the summation is to be done first for all the harmonics $n$ of any one phase and then for all the $p$-phases.

Now equation (4) is identical with equation (2) and should yield similar results except for the following two points of difference:

(1) $\phi_n$ in equation (7) now becomes $\phi_n'$.

(2) $E_n I_n$ in equation (7) has to be divided by $n$ because $X_L$ varies as the order of the harmonic. Consequently the current flowing through the voltage element of the wattmeter is $(1/n)$ times that flowing through the non-inductive resistance element.

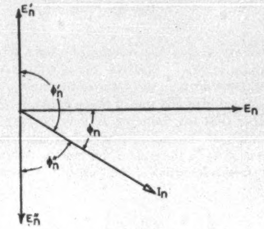


FIG. 8

With these two modifications equation (4), after integration, reduces to:

$$P_r' = \sum_p \sum_n \frac{E_n I_n}{n} \cos\phi_n \qquad (8)$$

Similarly equation (5) reduces to:

$$P_r'' = \sum_p \sum_n nE_n I_n \cos\phi_n'' \qquad (9)$$

Now in order to find the relation between $\phi_n$, $\phi_n'$ and $\phi_n''$ refer to Fig. 8, and note that:

$$\left.\begin{aligned} \phi_n' &= 90^\circ + \phi_n \\ \phi_n'' &= 90^\circ - \phi_n \end{aligned}\right\} \qquad (10)$$

Hence:

$$\left.\begin{aligned} \cos\phi_n' &= -\sin\phi_n \\ \cos\phi_n'' &= \sin\phi_n'' \end{aligned}\right\} \qquad (11)$$

Substituting equations (11) in (8) and (9) and the latter in (6) we have:

$$P_r = \sqrt{\sum \frac{E_n I_n}{n} \sin\phi_n \sum nE_n I_n \sin\phi_n} \qquad (12)$$

Expanding equation (**12**) we obtain:

$$\left.\begin{aligned} P_r &= \sqrt{\sum E_n^2 I_n^2 \sin\phi_n + \sum\left(\frac{m}{n}+\frac{n}{m}\right) E_m I_m E_n I_n \sin\phi_m \sin\phi_n} && (\mathbf{a}) \\ &= \sqrt{(\Sigma\, E_n I_n \sin\,\phi_n)^2 + M^2} && (\mathbf{b}) \end{aligned}\right\} \qquad (\mathbf{13})$$

The following has been suggested as a possible definition of reactive power:

$$P_r' = \Sigma\, E_n I_n \sin\,\phi_n \qquad (\mathbf{14})$$

Squaring equations (**13b**) and (**14**) and subtracting we have:

$$M^2 = P_r^2 - P_r'^2$$

$$= \sum\left[\,2 - \left(\frac{m}{n} + \frac{n}{m}\right)\right] E_m I_m E_n I_n \sin\phi_m \sin\phi_n \qquad (\mathbf{15})$$

The value of $M$ (equation (**15**) ) depends upon the following:

1. The order of the harmonics $m$ and $n$.
2. The magnitudes of the harmonic voltages and currents.
3. The values of $\sin\phi_n$ and $\sin\phi_m$.

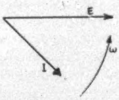


Fig. 9

It must be observed that $M$ is a summation of a set of products any one of which might be positive, negative or zero and that the value of $M$ depends upon the value of the summation and not upon the special value of any one of these products. It is, therefore, conceivable that the value of $M$ may be very small even though the values of the separate terms in the summation be large. This occurs when the sum of the positive terms (equation (**15**) ) is approximately equal to the sum of the negative terms. Now since

$$\left(\frac{m}{n} + \frac{n}{m}\right) \geqq 2$$

any one term in the summation will be positive if $\sin\phi_m$ and $\sin\phi_n$ have opposite signs and negative if they have the same sign.

The definition of reactive power (equation (**13**) ) is open to the least objections of any, so far proposed, for the following reasons:

1. The method of measuring $E$ and $I$ is practical because line voltages and currents are obtained easily and power is obtained according to the standard practice except that each wattmeter has to have three voltage elements instead of just one.

2. To the practical engineer the method of computing reactive power from the readings so obtained is very simple. (See equation (**6**) .)

3. Since equation (**14**) is a purely arbitrary definition of reactive power, and since it is open to objections from the standpoint of measurement, there appears no reason why equation (**13**) which is equally arbitrary but easily measurable should not be adopted as *the* definition of reactive power.

4. Equation (**13**) does not presuppose the resolution of nonsine waves into their harmonics before reactive power can be determined as is the case with equation (**14**).

5. Equation (**13**) is not open to the objections, both theoretical and practical, to which the A.I.E.E. standard definition is open.

The power factor of a polyphase circuit is defined as follows:

$$\text{Power factor} = \frac{P}{\sqrt{P^2 + P_r^2}} \qquad (\mathbf{16})$$

Where $P$ is the power measured (Fig. 5) by using the non-inductive resistance $R$ in the voltage element and $P_r$ is defined through equation (**6**).

**B. E. Lenehan:** It is customary to represent the cyclic variation of the instantaneous values of an alternating voltage or current by the projection of a line rotating once a cycle on one of the axes. Usually the vertical axis is chosen. The vector diagram, as commonly constructed, shows the relative positions of these lines at one point in the cycle. Usually one vector is most important and is directed horizontally to the right and called the reference vector. Fig. 9 is a vector diagram of an inductive circuit taken at the time the voltage is passing through zero in an increasing direction.

Power, as is shown in the papers, has two components; a steady value, and an alternating component of double frequency. Fig. 10 shows a set of such vectors at the same instant of time as in Fig. 9. The point $A$ corresponds to voltage zero and $B$ to current zero. At these points, the power input to the circuit obviously is zero. If we try to locate the point in the power cycle where the instantaneous reactive power, as defined by Professor Lyon, is zero, we encounter difficulties. Obviously, it is zero when the current in the inductance is zero. In a series circuit, this is point $B$ in Fig. 10. In a parallel circuit, the instantaneous reactive power is zero when the voltage is zero, which is point $A$ in Fig. 10. It is found that in order to evaluate the vertical component of the stationary part of the power vector, we must know the details of the circuit. However, the rotating part of the power vector is not dependent on the circuit details.

For an inductive circuit, this component has the direction of $P - jQ$ when voltage is used as reference and $P + jQ$ when current is used as reference, which is entirely in agreement with common practice.

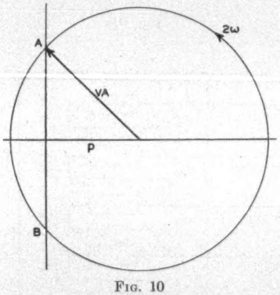


Fig. 10

Until we standardize on using either voltage or current as a reference vector in making vector diagrams, there is no choice between $P + jQ$ and $P - jQ$ for inductive loads. When the reference vector is chosen, the sign of $Q$ is or should automatically be determined. It is the same in direction as the vector not used as reference. If the components of the voltage and current vectors are taken on the horizontal axis instead of the vertical axis, the sign will be the same as that of the current or voltage vector.

**H. S. Baker:** At the present time it is quite customary to use certain meters to measure a certain quantity which we have been unauthoritatively calling "reactive volt-amperes." From this we have built up the custom of calculating what we have been unauthoritatively calling "power factor."

Now since it appears impossible to define the exact meaning of reactive volt-amperes or power factor as applied to complex circuits of bad wave form, and since there is no hope of such a definition being of any practical use (even if agreed upon), should we not continue to do our metering and billing in the customary manner but use some other terms (if necessary) than reactive volt-amperes and power factor for those physical quantities now actually measured and used in billing?

**W. M. Goodhue:** Professor Lyon in his paper refers to the "Concept of Instantaneous Reactive Power." Now this is identically the instantaneous *power* of the quadrature component of current, etc. Does this not suggest that it is the duty of reactive power *not to supply* energy storage but to *circulate* instantaneous power (since the average of the reactive power is zero)? In common with the viewpoint just stated, there is the practical occurrence of large circulating reactive-power of transformers on the "pump-back test" (with lagging or leading secondary currents), where the amount of stored energy involved (mainly the fluxes in the transformers) is negligible on considering the enormous reactive power in the primary and secondary loops. In this example, the reactive power actually is traveling in an endless chain composed of both primary and secondary lines (as links) joined together at each end by the transformers. Mathematically, reactive power will of course be defined in a special way to expedite circuit analysis; in particular the term quadrature volt-amperes is significant.

It is stated in the paper that a potential of one frequency and a current of another frequency produce neither active nor reactive power. That statement begs the question, being dependent on definition; particularly, it is possible to have magnetic stored energy produce reactive power between voltage and current of two different frequencies even in a linear system. For example, a rectifier smoothing inductance has an *enormous* instantaneous power between the *direct-current* and the *alternating-current* voltage (the voltage ripple impressed on the inductance), which may amount to 20 times the ordinary *alternating-current* reactive power between the alternating-current component (the current ripple), and the alternating-current voltage. This power is *circulated* between the inductance and the alternating-current line, through the rectifier. Since, as explained, reactive power means fundamentally the circulation of the portion of instantaneous power having zero average value, the direct current—alternating-current voltage instantaneous power *is* a reactive power, in this case, of a magnetic field, and to avoid confusion, may well be named *cross-reactive* power. On the alternating-current line supplying the rectifier, this cross-reactive power appears again, this time between harmonics (higher than fundamental) of the line current and the fundamental of the voltage (phase of equivalent $Y$). The change between the two kinds of cross-reactive power is of course physically performed by the rectifier itself.

Summing up, there should be three kinds of reactive power, fundamental (lagging, leading), cross-reactive power, and harmonic reactive power (between components of the same frequency if existent); any of the three may be caused by energy storage of various kinds (including mechanical inertia), *or may circulate in an endless path.*

The first, or ordinary fundamental component type, is concerned, practically speaking, with excitation, and the power factor definition in terms of total ordinary reactive power may well be called the *excitation factor:*

Excitation factor =

$$\frac{\text{total active power}}{\sqrt{(\text{total active power})^2 + (\text{total reactive power})^2}}$$

The other two kinds, cross-reactive power and harmonic-reactive power, are concerned vitally with the heating effects (copper loss, and core loss) and so affect the *ratings* and cost of equipment. On the basis of heating, there is an interesting definition of power factor of a three-phase line:

$$\text{Power factor} = \frac{\sqrt{3}\,P}{\sqrt{I_A^2 + I_B^2 + I_C^2}\ \sqrt{V_A^2 + V_B^2 + V_C^2}}$$

where

$P$ = total power, all 3 phases
$I_A$ etc., are line rms currents
$V_A$ etc., are line rms voltages

Assuming an alternator having equal stator copper resistances, the stator copper loss is proportional to $I_A^2 + I_B^2 + I_C^2$ in the presence of both harmonics and quadrature currents. The core-loss and field loss (due to main flux, *not* armature reaction), tend to vary as the voltage squared (true for linear systems), so that $V_A^2 + V_B^2 + V_C^2$ is used for symmetry and simplicity of the formula.

**S. H. Wright:** Considering reactive power from the system operator's standpoint, the writer firmly believes that much is to be gained in system operation by treating all reactive power as inductive-reactive power—as described by Mr. Johnson.

Considering reactive power from the viewpoint of those engineers who deal with calculations involving vector diagrams and complex numbers, there is divided opinion as to whether inductive- or capacitive-reactive power shall be taken as $+jQ$. The following discussion of this matter emphasizes a fundamental concept which the writer believes should be given considerable weight in coming to a conclusion. This same concept is described in different form in Doctor Fortescue's paper; it is believed that the following presentation will aid in giving a clear concept of the fundamentals involved. Discussion is limited to single-phase quantities and pure sine waves.

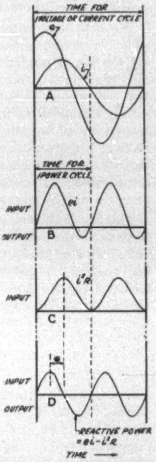


FIG. 11

A—Voltage and current waves
B—*ei* (instantaneous) power wave
C—$i^2R$ power wave
D—(Inductive) reactive power wave = $ei - i^2R$
*Wave of inductive reactive power leads the $i^2R$ wave by ¼ of a power cycle.

Consider an air-core reactor having resistance and inductive reactance of the same order of magnitude. Apply voltage $e$, obtaining current $i$, as in Fig. 11A. Determine the variation of (instantaneous) power with time, such as by an instantaneous power element of an oscillogram, obtaining Fig. 11*B*. There is nothing fictitious about the power wave in Fig. 11*B*. It is not only the product of instantaneous values of $e$ and $i$; it is an indisputable record of power, which, it is noted, is predominately input but periodically output.

Let us now separate this power wave into two components. The $i^2R$ component is known to be the wave in Fig. 11*C*, which is in phase with the current wave. Let us subtract this $i^2R$ wave in Fig. 11C from the total power in Fig. 11B, obtaining the wave in Fig. 11D which obviously is the wave of reactive power. In other words, the two components, $i^2R$ in Fig. 11C and reactive power in Fig. 11D, when added give the total power in Fig. 11B.

It is evident that a power cycle is half as long as a voltage or current cycle. It also is evident that the *reactive power wave leads the $i^2R$ wave by one-quarter of a power cycle.* Similarly, it can be shown that for a circuit containing resistance and capacitance, the reactive power wave *lags* the $i^2R$ wave by one-quarter of a power cycle.

In view of the above, it appears fundamental and logical to designate inductive reactive power as $+jQ$.

**W. H. Pratt:** The problem of the measurement of the various derived quantities that are discussed in the papers involves a deeper examination of them than is indicated by their convenient designation as $E$, $I$, $EI$, $\sqrt{E^2I^2 - P^2}$, etc.

While every form of electric manifestation is potentially a key to some measurement process, the number of electric quantities that can directly be measured is limited. This is due largely to the fact that many of the quantities we would like to measure do not occur naturally. When this is true, there is no such thing as direct measurement of such except in the sense that the simplest possible procedure shall have been chosen.

We can have currents that from instant to instant almost exactly represent other currents that form parts of our formulas. By the use of noninductive resistances, we can obtain currents that from instant to instant very closely represent voltages. By the use of highly inductive circuits, we obtain currents that closely represent the indefinite time integral of a-c voltage, while by the use of capacity, currents representing the derivative of voltage with respect to time are secured. By combinations of derived circuits, higher integrals and multiple derivatives may be represented by currents. Similarly, integrals and derivatives of currents may be represented by other currents.

The instantaneous product of pairs of simultaneous values is secured by the reaction between simultaneously occurring fields. Integration of products and averaging may be secured by utilizing mechanical inertia or thermal capacity. Ordinarily the former gives the more vivid response. Thus, if we would secure the value of $I$, the operation corresponds to

$$\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}$$

and every element in this formula is represented in the measuring device, two fields each, from instant to instant, proportional to the value $i$, their product by the mutual reaction of these fields, integration and averaging by the inertia of the moving system of the measuring instrument, and finally the extraction of the square root by the arrangement of the marking on the scale.

To measure such quantities as $EI$, or voltampere-hours, or $\sqrt{E^2I^2 - P^2}$ the problem becomes increasingly complicated. So far as measurement is concerned, the expressions given in the preceding sentence are only titles. If we would see what is involved, they must be written in terms of the fundamental quantities that are accessible in the circuit.

Thus:

$$EI = \sqrt{\frac{1}{b-a}\int_a^b e^2\,dt}\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}$$

voltampere-hours =

$$\cdots\cdots\frac{1}{h-g}\sum_g^h\left(\sqrt{\frac{1}{b-a}\int_a^b e^2\,dt}\sqrt{\frac{1}{b-a}\int_a^b i^2\,dt}\right)\Delta t$$

The $\Delta t$ signifies that while the time must be finely subdivided the quantities within the parenthesis can hardly be considered as having instantaneous values.

$$\sqrt{E^2I^2 - P^2} = \sqrt{\frac{\int_a^b e^2\,dt}{b-a}\cdot\frac{\int_a^b i^2\,dt}{b-a} - \left(\frac{\int_a^b ei\,dt}{b-a}\right)^2}$$

It seems almost impossible to set up a corresponding expression for the general case of reactive volt-amperes. This implies that exact measurement of it may be impossible. For the restricted cases that are ordinarily measured, assumptions are made outside the formula, which resembles that for power.

Relatively simple mechanisms are available for performing all the operations that have been so far indicated, but their assembly to effect a measurement such as $\sqrt{E^2I^2 - P^2}$ makes a very imposing array. Nevertheless unless approximations, often dangerous, are accepted, every element, quantity, and operation, must be correctly represented in the measuring device.

The bearing of the foregoing on the present problem is this: Many of the quantities that are being discussed look so innocent yet are in fact so complicated that their practical realization as measured quantities is not likely to be undertaken except under exceptional circumstances. If then, without a sacrifice of fundamental accuracy of conception, a choice is possible, the simpler should by all means be chosen. It will be complicated enough.

**Arthur A. Bolsterli:** To the practical engineer who views reactive power and power factor chiefly in their commercial aspect and who is not unaware of the difficulties encountered in trying to acquaint power customers with the elusive and to them wholly mysterious concepts of power factor and reactive power, the multiplicity of facts and aspects presented in the symposium must be little short of bewildering. Did any of the familiar concepts stand the acid test of scientific scrutiny and how is the matter to be explained to the power consumer in the future?

To anyone, however, who has been following the discussions carried on during the last few years under the leadership of the Roumanian group of engineers the divergence of views in evidence in the symposium is less surprising. The subcommittee on reactive power is faced with issues of singular intricacy. While the commentary to the Roumanian questionnaire has illuminated the problems involved from many angles, the symposium throws new light on them, and even though the conclusions arrived at in the various papers seem still far from being unanimous, it is nevertheless evident that progress is being made towards ending the deadlock that came into being when the International Electrotechnical Commission in its 7th general meeting at Stockholm in 1930 rejected all the proposals for the definition of reactive power.

The subject is presented in the symposium in turn from the point of view of power dispatching, circuit analysis, and metering. It is unfortunate that the viewpoint of power economics should not have been presented with equal weight, as it is second to none in practical importance.

It is clear, for example, that whatever the eventual definition of reactive power will be, it will not materially affect the power dispatcher, because he can neglect with impunity the refinements around which the whole argument revolves. For this reason power dispatching as a viewpoint cannot contribute materially towards finding the correct answer to the arguments.

Power economics on the other hand has a decisive bearing upon the subject. In fact it is necessary, as Professor Lyon points out, to decide at the outset as to whether the definitions sought shall serve primarily the commercial ends of power economics or the scientific aims of circuit analysis.

In my opinion the choice is not entirely open. Both Professor Smith's and Professor Lyon's presentations, although largely concerned with circuit analysis, fail to suggest solutions that radically solve all difficulties.

Professor Smith essentially subscribes to Budeanu's proposals which have been widely discussed abroad. Professor Lyon concludes that power factor is useless in circuit analysis in the general case. Equally useless is for these purposes the concept of resultant reactive power for all frequencies combined. The conclusion seems warranted that circuit analysis not only can do better without the concepts whose definitions are sought, but does not furnish a basis for logical or even convenient definition.

The only alternative left seems therefore to attempt these definitions by leaning on the clues found in power economics, even though this may result in relegating power factor to the plebeian neighborhood (using Mr. Knowlton's expression) of load factor, etc.

Before elaborating further on this last aspect a short discussion is given on Professor Smith's paper. The introduction of distortion power is an ingenious mathematical artifice to restore, in the general case, the orthogonal relation that exists between apparent power, reactive power, and real power in the case of the sinusoidal single-phase circuits. The fact that three-dimensional space has to be resorted to for representing the new relation offers no practical difficulties.

Professor Budeanu's concepts, advocated by Professor Smith, are of real practical value in those cases where either the voltage or the current is sinusoidal, while the other quantity is non-sinusoidal. It is a coincidence that an apparatus whose current is non-sinusoidal, but whose impressed voltage is generally sinusoidal, is becoming increasingly important, namely, the mercury arc rectifier. It is amenable to analysis by this method which consequently assumes considerable importance. Attention is called to an article by H. Rissik[1] where this application is treated exhaustively.

If both current and voltage are non-sinusoidal the concept of distortion power becomes devoid of physical meaning as well as elusive to measurement, representing, as it does, a sum of products of the rms values of voltage and current harmonics of different frequencies. Its introduction nevertheless is necessary as a mathematical expedient if reactive power is defined as suggested in Professor Smith's paper and the orthogonal relation $(EI)^2 = P^2 + P_f^2$ is to be retained. As the distinction between reactive power and distortion power is at best arbitrary in the general case, and both can be determined only by the laborious process of harmonic analysis of oscillograms, the difficulties of applying the new concepts to power loads are easily realized.

It is apparent that the necessity for the concept of distortion power is the result of a compromise necessary if the fundamental relations that hold true for reactive and apparent power in the sinusoidal case are to be preserved and expansion into Fourier series is resorted to in tackling the general case. Once this is realized the ground will be cleared for a truly general attack on the problem that is not prepossessed by concepts specifically adapted to sinusoidal circuits. A significant step in this direction has been made by S. Fryze[2] who has developed for the case of single-phase circuits the relations between current and voltage and their products without restriction as to wave shape, except that both current and voltage are periodic functions of time:

$$e = f(t) \qquad i = g(t) \qquad \text{period} = T$$

This manner of analysis presents a novel viewpoint and is believed to be of sufficient importance to justify a brief description hereunder.

The underlying idea is to start from well defined and easily measurable quantities only and do without Fourier series.

After defining the rms values of voltage, current, and power, by formula identical with those given on the first page of Professor Lyon's paper, Fryze defines the power factor as

$$\lambda = \frac{P}{EI} \qquad (1)$$

where $P$ is real power (average over cycle) and $I$ and $E$ are the rms values of current and voltage. From a mathematical theorem ("Ungleichung von Schwarz") it follows directly that the power factor defined by (1) obeys the relation:

$$\lambda \leqq 1 \qquad (2)$$

and that the condition for its reaching unity value is:

$$\frac{e}{i} = R = \text{const.} \qquad (3)$$

or in other words, the power factor becomes unity when, and only when, at every instant, the current is proportional to the voltage, *i.e.*, when the current and voltage waves have the same shape. If the ratio of simultaneous instantaneous values, as expressed by (3), is not constant, but a function of time, the power factor must need be smaller than unity.

Both current and voltage are now resolved into a real and a wattless component, whereby the wattless component of current, for example, is characterized by the condition that its product with the instantaneous voltage integrated over a complete period is zero. The partial functions thus obtained are found to be orthogonal, and by forming their rms values the validity of the quadratic equations:

$$E^2 = E_p^2 + E_w^2 \qquad (4)$$

$$I^2 = I_p^2 + I_w^2 \qquad (5)$$

as well as

$$P_{ap} = P^2 + P_w^2 \qquad (6)$$

is established, in spite of the fact that both voltage and current are of quite general wave shape.

In order to arrive at a physical interpretation of these formal equations, Fryze proceeds to investigate the functions: $p = ei$ and $r = \frac{e}{i}$ which he resolves into wattless and power components and then integrates over a period. The resulting equations show that the general alternating-current load can be represented by the series or parallel connection of two elements of load, one of which behaves as a constant resistance whose value is determined solely by $P$ and $I$ (or $E$), while the other has the character of a periodically varying resistance having a value determined by $P_w$ and $I$ (or $E$). The former is termed the "active" element of load, the latter the "wattless" element of load. The wattless element of load is characterized by the fact that its energy consumption over a complete period is zero, and the general expression for wattless power is represented by the product of the rms values of current and voltage across the terminals of a wattless element of load. The investigation stops at these terminals as the rational boundary and does not inquire into the question as to whether the wattless power of the load is due to variable resistance, to the presence of electric or magnetic fields, or to counter emf's.

The quantity $P_w$ in Fryze's analysis has the same meaning as that known as wattless, idle or reactive power in the case of sinusoidal wave forms. In terms of Professor Smith's terminology for the non-sinusoidal case, Fryze's "wattless" power corresponds to "fictitious" power. As the orthogonal equation

$$P^2 + P_w^2 = P_{ap}^2$$

follows quite naturally, the necessity of distinguishing between a distortion and a reactive component of fictitious power—which is impossible of practical attainment in the general case—is obviated.

Apparent power, real power, and wattless power are again combined to a rectangular triangle, as in the sinusoidal case, with the difference that the angle no longer represents a phase displacement. The International Electrotechnical Commission definitions drawn for sinusoidal currents (7th general meeting 1930) become at once applicable to the general case.

In Fryze's analysis the positive (capacity) and negative (reactance) character of wattless power no longer exists in the sense it does for the sinusoidal case.

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[1] *Journal I.E.E.*, May 1933, vol. 72, p. 435.

[2] *E.T.Z.*, vol. 53, 1932, pp. 596, 625, 700.

As the sole criterion for the presence or absence of wattless power emerges equation (3), *i.e.*, wattless power is present unless current and voltage have the same wave shape. The term wattless power is here preferred as it is more descriptive than fictitious power and as the term reactive power should be reserved to the special case where wattless power is due solely to reactance.

It is concluded further than an infinite number of voltage and current wave shapes will result in the same rms values and the same power factor.

The extension of Fryze's method to the general polyphase load should meet with great interest.

The correlation between the above analysis and power economics becomes apparent when the problem is investigated as to what relation must exist between the general wave forms of current and voltage if a given power is to be transmitted through a circuit of constant resistance with the condition attached that the losses shall be a minimum.* It is significant, and no mere coincidence, that this relation turns out to be identical with the condition derived by Fryze (equation (3) of this discussion), for the absence of wattless power.

Thus wattless power in its most general form is shown to be the cause of extra losses in the transmission of power. Power factor is found to represent a measure of power efficiency in transmission and distribution, the utilization factor of a given circuit. Both power factor and its concomitant, wattless power, owe their importance to the economics of power transmission. It now turns out that in their very essence the economic element is less elusive than the physical.

**R. G. Lorraine:** Articles appearing in contemporary literature show a surprising difference in point of view from which the sign of inductive reactive power (inductive volt-amperes) may be determined and about an equal division between those favoring a negative sign and those opposed to it. Even the four papers presented at this symposium which specifies a convention are equally divided. However, it is recognized by all that a single convention is desirable.

The proper sign of reactive power caused by the presence of inductance in a circuit should emerge of itself from a consideration of the previously adopted conventions for fundamental quantities. These are:

1. The algebraic conventions for complex quantities and direction of rotation of time vectors.
2. Definition of impedance as

$$Z = R + jX$$

where $X$ is positive for an inductive reactance.

As a corollary, admittance ($Y$) is

$$Y = \frac{R}{Z^2} - j\,\frac{X}{Z^2}$$

Then power $P$ may be expressed as either

$$P = E^2Y = E^2\,\frac{R}{Z^2} - jE^2\,\frac{X}{Z^2}$$

or

$$P = I^2Z = I^2R + jI^2X$$

depending upon whether the voltage $E$ or the current $I$ is used as the original reference axis. Thus the sign of inductive reactive power correctly may have either a negative or a positive sign but, to avoid confusion, one sign should be established arbitrarily.

The reasons which have led to the practice of plotting inductive reactive power with a negative sign may be summarized as follows:

1. The great preponderance of networks in which the voltage is known as a function of time has led to a prevailing preference for a voltage reference vector (in voltage-current diagrams).
2. The established convention of counter-clockwise rotation to indicate the positive progression of vector quantities in time requires that leading quantities be represented as counter-clockwise and lagging quantities as clockwise relative to the reference vector. The significance of leading and lagging power factor is established by this convention.
3. The significance of leading and lagging power factor carried over to the power diagram makes capacitive reactive power positive.
4. Since power and reactive power at equal voltages are proportional to the corresponding currents and when expressed as per unit quantities are equal in magnitude, it is desirable that the corresponding complex numbers of current and power have the same sign.

The last consideration is of great convenience in network calculations.

There are, of course, situations in which it is more convenient to express inductive reactive power as positive, usually when current is used as a reference vector with series circuits. For these occasional cases the most convenient practice should be followed and it should be stated clearly that inductive volt-amperes are taken as positive.

In conclusion, it is believed that inductive reactive power should be taken with a negative sign. However, because of the wide divergence of opinion at the present time, some latitude in the use of this arbitrary convention should be allowed. Therefore, it should be limited to unspecified power equations and diagrams.

**C. F. Bowman:** In developing the complex expression for power in the form $\dot{P} = P \pm jQ$, we find that the product as we would be inclined to use it, $\dot{P}' = \dot{E}\dot{I}$ has no physical significance unless we use either $\dot{E}$ or $\dot{I}$ as the reference in writing the expressions we multiply. This can be shown analytically, but its failure to check can be shown sufficiently by an example. Using Euler's identity for brevity e.g., [$\dot{E} = E\,(\cos\phi \pm j\sin\phi) = Ee^{\pm j\phi}$ we may assume a voltage $Ee^{j\frac{3\pi}{8}}$ and a current $Ie^{j\frac{\pi}{8}}$; whose product we find as ($\dot{E}\dot{I} = EIe^{\left(j\frac{3\pi}{8} + j\frac{\pi}{8}\right)} = EIe^{j\frac{\pi}{2}}$). This 90 deg phase relation indicates a purely reactive power; yet with the actual phase difference between current and voltage being $\dfrac{\pi}{4} = 45$ deg, we know that the power factor is 0.707.

To give the product physical significance it is necessary, as stated heretofore, to use these terms so as to utilize either $\dot{E}$ or $\dot{I}$ as reference for the product. This can be done by reversing the sign of the Euler exponent (or of the $j$-term in the complex expression) in the quantity we wish to utilize as the reference. Using this method for the example given above with an inductive impedance, and electing to use voltage as reference, we reverse the sign of the voltage angle and multiply, obtaining:

$$\begin{aligned}\dot{P} = \dot{E}\dot{I}\,]_E = EIe^{j\left(-\frac{3\pi}{8} + \frac{\pi}{8}\right)} = EIe^{-j\frac{\pi}{4}} &= EI(\cos 45^\circ - j\sin 45^\circ)\\ &= P - jQ\end{aligned}$$

Hence, utilizing voltage as reference we find that $-jQ$ represents inductive power, and $+jQ$ would represent condensive power.

It would be equally correct, mathematically, and equally simple, to elect current as the reference, thereby reversing the sign of the lateral term, $jQ$. With practical circuits, however, we find that there is a deep rooted association of the term "lagging" with inductive circuits based on the lagging currents there found (though it might equally as well have been associated with the lagging voltage of condensive circuits). This habit, in turn, comes from our choice of voltage as reference in our modern systems of distribution by multiple circuits: the voltage is common to all branches and hence the most convenient reference.

Hence to be consistent with our present tacit assumptions of voltage as reference, the negative sign should be used with inductive power as well as with inductive currents.

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*Rissik, *loc. cit.*

This definition must be used to be consistent with the A.I.E.E. definition of phase power, reactive: $P_r = EI \sin \phi$ if we maintain voltage as our reference. In this case, for inductive circuits, $\phi$ is negative, $[\sin(-\phi)] = [-\sin\phi]$; and for an inductive circuit this gives $\dot{P} = P - jQ$.

For the multiple circuit and voltage reference, we find this negative sign for inductive quantities carries down also to the circuit elements, and $\dot{I} = \dot{E}(|G| - j|B|)$. The impedance, $\dot{Z} = r + jx$, is essentially a series circuit quantity where the reference is current; and if current is to be established as a reference with one of the groups of quantities involved, it should be carried through consistently. If this is done, the sign of the lateral term is positive for inductive quantities throughout.

If the inductive power is assigned the negative sign, we retain our unifying concept of the voltage as reference and can associate the term "lagging" with inductive quantities in power as well as admittances and currents.

**P. L. Alger:** The various conceptions of reactive power presented in recent committee reports and in papers in ELECTRICAL ENGINEERING illustrate how differently we can view the most familiar elements of electrical theory, while Doctor Silsbee's analysis[3] of possible reasons for selecting the sign of reactive power indicates how difficult it is to agree on even the simplest conventions. Doctor Silsbee leans to the choice of a positive sign for inductive volt-amperes on the basis of general principles of scientific convention. Mr. J. A. Johnson reaches the same conclusion on the basis that inductive power is commonly generated and distributed just as real power is, so that it is convenient to use the same sign for both. On the other hand, numerous writers consider inductive power as negative for the same reasons that inductive currents are called lagging and are plotted downwards, while Mr. A. E. Knowlton's reported questionnaire shows 50 representative engineers to be about equally divided in opinion.

Clearly, no agreement is possible unless a conclusion can be reached from universally accepted definitions without bringing in any assumptions whatever.

What is the physical meaning of the angle between the active and reactive power vectors? Active power flows continuously in the same direction in each conductor of the system, while reactive power flow alternates in direction in each conductor at double line frequency. The combination of active and reactive power is, therefore, exactly analogous to that of the direct and alternating components of a pulsating unidirectional current. In each case the 2 quantities have different frequencies, and so can not properly be represented by vectors in a common time diagram. No physical reality can be ascribed to the angles in a right-angled triangle representing the a-c and d-c components of a pulsating current. However, the right-angled triangle representing the active and reactive volt-amperes in an a-c system is geometrically identical with the representation of the in-phase and out-of-phase components of voltage or current in the same system.

By universally established conventions, an inductive impedance is represented by the expression:

$$Z = R + jX \tag{1}$$

which results in the expressions:

$$V = (R + jX)\, I \tag{2}$$

for the vector voltage referred to the current as reference axis and

$$I = \left( \frac{R - jX}{R^2 + X^2} \right) V \tag{3}$$

for the vector current referred to the voltage as reference axis.

In dealing with constant current systems, it is the general practice to use equation (2), and hence to represent inductive voltages as positive. The vector diagrams so obtained represent active and reactive power equally as well as in-phase and reactive voltages.

In dealing with constant voltage systems, it is the practice to use equation (3), and hence to represent inductive currents as negative. These vector diagrams equally well represent active and reactive power as they do in-phase and inductive currents.

Whatever system is being considered, vector diagrams of voltages and currents are useful and are generally employed. It is obviously convenient to use the same diagrams to represent the power relations. In fact, it seems ridiculous to do otherwise, as the diagrams are geometrically identical, and as no physical reality can be attached to the angles in the power triangle considered by itself. The angles in the current and voltage triangles represent time phase in degrees, or in fractions of a cycle.

It is thus apparent that inductive volt-amperes should be defined as positive, to match the inductive voltage, (equation 2) if the current is considered as reference axis. This is the normal convention for constant current systems. Also, inductive volt-amperes should be defined as negative, to match the inductive current, (equation 3) if the voltage is considered as the reference axis. This is the normal convention for constant voltage systems.

Both conventions are equally acceptable and equally in accord with the already well established standards. Hence, both must be permitted, and the only possible grounds for selecting one as standard are convenience and usage.

The very great predominance of constant voltage systems in power transmission and other cases where reactive power diagrams are of practical interest makes it convenient to adopt as standard the convention of plotting inductive power as negative. A review of the literature indicates a gradual trend of usage toward the negative sign for inductive volt-amperes, although the total number of references is about equally divided.

If it is realized that vector power diagrams have no physical reality, but are simply representative of currents or voltages, no difficulties can arise, but it is obvious that whether currents or voltages are implied it must always be stated. If, as Doctor Silsbee has done, we attempt to define the sign of reactive power from a logical analysis of the underlying definitions, we are immediately involved in such questions as whether the susceptance, $B$, is $\dfrac{X}{Z^2}$ or $-\dfrac{X}{Z^2}$, and the discussion loses all physical significance.

An over-excited synchronous generator delivers inductive volt-amperes, and is properly called a lagging power factor generator. An under-excited synchronous motor receives inductive volt amperes from the system, and is so properly called a lagging power factor motor. With the standard counterclockwise rotation of vectors, the term lagging definitely connotes a downward plotted, or negative vector.

The evidence presented here from the points of view of both convenience and usage, therefore, indicates that inductive volt-amperes should be considered negative. If, however, it is desired to use the current as a reference axis and take inductive volt-amperes positive, this is just as correct and legitimate as it is to treat the power of a motor as positive. The real difficulty with reactive volt-amperes is that they have 2 signs, one for angle of lead or lag and one for inflow or outflow. The resultant signs for the usual types of power flow recommended as standard are thus as indicated in the following table.

| Apparatus | Power | Reactive volt-amperes |
|---|---|---|
| Over-excited synchronous motor | − | − |
| Under-excited synchronous motor | − | + |
| Over-excited synchronous generator | + | − |
| Under-excited synchronous generator | + | + |

**Wm. B. Nulsen:** Volt-amperes is necessarily a vector quantity having a real component and a quadrature component, or if you wish, an active component and a reactive component.

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3. ELECTRICAL ENGINEERING, April, 1933, pp. 261-2.

Thus in the expression $\underset{\cdot}{VA} = P \pm jQ$, $P$ is the active component and $Q$ is the reactive component. The term power is generally understood to mean watts, or the active component of the volt-amperes, and with this understanding the term "reactive power" is meaningless.

It is certainly advisable to give a name to the reactive component of volt-amperes. The standardization of such a name is of more importance than the name itself, although the unit "var" seems most appropriate, indicating as it does, reactive volt-amperes.

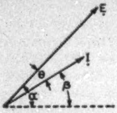


FIG. 12

Mathematically, the sign of the quadrature component depends upon whether we consider $\theta = \alpha - \beta$, or $\theta = \beta - \alpha$, in Fig. 12. In the first case $\theta$ is measured from $\underset{\cdot}{I}$ to $\underset{\cdot}{E}$, and in the second case $\theta$ is measured from $\underset{\cdot}{E}$ to $\underset{\cdot}{I}$, with a consequent reversal in the sign of sin $\theta$. This is identical with the effect of the order of vectors when taking vector cross-products, so that $\underset{\cdot}{E} \times \underset{\cdot}{I} = -\underset{\cdot}{I} \times \underset{\cdot}{E}$.

The angle of lag or lead is understood to be the angle which the current vector makes with the voltage vector, *i.e.*, the current vector is referred to the voltage vector. Thus the angle $\theta$ should be measured from the voltage vector to the current vector, and it becomes a negative angle with a lagging current, and a positive angle with a leading current. Vars are therefore negative with a lagging current, and positive with a leading current.

The question of clockwise or counter-clockwise rotation does not enter directly into the choice of signs, since the double frequency volt-ampere vector has no more place on our Argand diagram than have the stationary impedance or admittance vectors. However, if we consider vector volt-amperes on a separate diagram, there appears to be a consistency in associating $-jQ$ with a lagging power factor and $+jQ$ with a leading power factor. This is in agreement with the convention just outlined.

Letting $\underset{\cdot}{E} = (e_1 + je_2)$, and $\underset{\cdot}{I} = (i_1 + ji_2)$, we may write

$$\underset{\cdot}{VA} = (e_1 i_1 + e_2 i_2) + j\,(e_1 i_2 - e_2 i_1),$$

and using vector notation

$$\underset{\cdot}{VA} = \underset{\cdot}{E} \cdot \underset{\cdot}{I} \pm j\,|\,\underset{\cdot}{E} \times \underset{\cdot}{I}\,|,$$

the sign of the quadrature component being determined as above.

**G. V. Mueller:** The writer votes emphatically for the principle of regarding lagging reactive power as negative, that is, drawing it downward from the right-hand end of the kilowatt base.

**H. K. Humphrey:** The presentations by Doctor E. B. Silsbee and J. Allen Johnson, of arguments for considering lagging reactive volt-amperes positive and plotting them upward in vector diagrams, ELECTRICAL ENGINEERING, April 1933, pp. 259-267, have convinced the writer that this "practical" convention (Silsbee's *IBa*) is better than the "academic," heretofore favored. Nevertheless, it certainly is natural to feel that volt-amperes partake more of the nature of amperes than of volts, and to wish that, in addition to the advantages of logical sequence set forth by Silsbee and of correspondence of meter readings given by Johnson, we might also find the volt-ampere vector falling parallel to the current vector. It may be worth while to search our memories for reasons why all these advantages may not be had; the search will carry us back to 1911, when our convention as to rotation of vector diagrams was adopted. Until then, there was not only the "crank" diagram which we now use, but another in which the vectors were conceived to be standing still with time progressing in the positive direction past them; in fact, the vectors merely were the diameters of the circles resulting from plotting the sine-wave quantities in polar coordinates. According to this convention, a lagging current was plotted upward, in the first quadrant. Considerable confusion resulted from the fact that about half the engineers used one of these conventions and the other half the opposite, so that in 1911 it was thought desirable to end this confusion for all time by adopting one or the other. At that time, there was no solid basis upon which a choice could be made; either method was a purely arbitrary convention having, in spite of the interesting though specious reasoning presented in argument, no advantage over the other except the habit of the individual user; indeed, each argument could be boiled down to something like, "I learned *this* convention, and it is perfectly clear to me that no other can be natural." Under these conditions, the matter was settled in the only way it could be fairly settled, that is, so as to disturb the smaller number of established habits. We can see now that it was unfortunate that the majority had learned the "crank" system, defended by Professor Kennelly; but the minority, led by Doctor Steinmetz, relearned their vector diagrams, and found that the task turned out to be easier than they had feared.

The real arguments came only years after the decision. There are two of these, it seems to me; one is the fact brought out above, that, were lagging current positive, then lagging reactive volt-amperes would naturally be positive, and would have naturally all the advantages claimed by Silsbee and Johnson, and in addition would look, in vector diagrams, like lagging current. The other advantage of the now discarded convention comes in the numbering of polyphase vectors to show phase-order. It is without doubt more natural to number these in the counter-clockwise order, just as we number the quadrants in trigonometry. This is not merely a quirk of my own mind, for each year I introduce the subject of unbalanced three-phase systems to students familiar with trigonometry and with crank diagrams; with this background only, they are asked to draw and number a set of three-phase vectors. This I have been doing pretty regularly since 1916, and invariably the result has been what we must call the negative or reverse phase-order. It would be considerably better if the natural order were positive and direct; had Doctor Steinmetz' convention happened to prevail, this would have turned out to be the case.

It seems that we made a bad bargain. We did get rid of the confusion due to the simultaneous existence of the two conflicting vector conventions, but it would have been better to tolerate that confusion for 7 or even 20 years; for now we must go on forever using unnatural volt-ampere diagrams and teaching students that their instincts, trained in trigonometry, are negative and reversed. I wish sincerely that I could feel that Doctor Silsbee's statement were not true: "The sign of $X$ is the result of purely arbitrary choice, made so long ago that there seems little need, or *hope*, of changing it." Yet I suppose that he is right, for much as I should like to, I hardly dare propose now that we go back and change all our vector diagrams again. But does not the situation in this matter emphasize the unwisdom of making an arbitrary choice too early, the wisdom of waiting until we can know where our choice will lead?

**V. G. Smith:** It has been said that the professorial group is almost unanimously in favor of calling reactive power due to leading current positive. The reason is not hard to find.

Fig. 13A shows a usual vector diagram with currents leading the voltage the details of which are fixed by accepted conventions. When it is desired to draw the corresponding power diagram it may be drawn either as in Fig. 13B or D. Fig. 13B clearly is preferable to D, because in appearance it is exactly similar to A. From one point of view the only difference between the current diagram and the power diagram is that the scales are different. Why, just because the current components are multiplied by the voltage should the diagram be inverted and the apparent rotation reversed?

Fig. 13D corresponds to C in which voltages are plotted with respect to a current. This type of diagram belongs to the series circuit in which the current is thought of as the cause of the potential differences.

It makes little difference to the man who is working with reactive power constantly which convention is chosen but it would be very confusing to students to have to use one convention for currents and the opposite, at least in appearance, for reactive power.

**H. W. Price:** It is remarkable that all the papers and discussions on what is to be measured and how to measure have been contributed only by engineers of electrical service companies and manufacturers of electrical equipment, and by men in standardizing and academic work. There has been no one to represent the millions of consumers of electrical energy, the great group whose payments make possible the entire electrical industry. The consumers should be represented.

In the writer's opinion there are two fundamental phases of the question of definitions of units, which should not be overlooked by any committee endeavoring to find final replacements for the old contradictory A.I.E.E. definitions:

1. Definitions of active and reactive powers and active and reactive energies for statutory authorization, chosen to include as accurately as possible the generalized case of non-sine waves of voltage and current, and unbalanced load in polyphase circuits. The unbalance might properly, if necessary, involve extra factors to be defined. The apparent tendency to base definitions on convenient approximate methods of metering is, in the writer's opinion, wrong. The fact that voltage usually is measured commercially by an ordinary voltmeter is no reason whatever against international definitions of voltage and the last limit of precision in national and international definitions of the volt.

2. Corresponding statutory working definitions with sufficient tolerance to cover the deficiencies of the present state of the art of metering in commercial circuits, having regard also to the fact that individual consumers usually cannot afford metering equipment quite suitable for a large manufacturing industry or a municipality.

The definitions under (1) should be as nearly as possible final, so that those working in theoretical and development fields may not be hampered by changing fundamental definitions. Definitions under (2) can be modified when necessary at long intervals as the art of accurate and economical measurement develops.

It is a fact that $n - 1$ ideally correct wattmeters properly connected in a circuit of $n$ conductors can correctly measure the average rate of transmitting "active" energy through the circuit, regardless of wave forms and unbalance. It is equally a fact that the very properties which enable the wattmeters to measure thus, by disregarding all fundamental and harmonic voltage and current products and cross products not contributing to active flow of energy, prevent them from measuring average rate of reactive flow of energy no matter how they may be connected. The meters that ignore such products when connected in one way cannot include them when connected another way. Nevertheless those products are properly to be included in reactive definitions because they cover flow of energy not contributing to "active" power. The definitions under (1) should cover our best understanding of physical facts related to flow of energy. The subsidiary definitions under (2) should include tolerance to cover practical needs of commercial measuring.

**H. Sohon:** In any single-phase load with sinusoidal voltages and currents there are certain physical magnitudes and certain convenient parameters that can be measured.

The physical quantities include: instantaneous voltage; instantaneous current; phase angle between voltage and current; instantaneous power; and average power.

The parameters include: effective current; effective voltage; apparent power; reactive power; and power factor.

The relations assigned to these various items give the well known power triangle. Any quantity in the power triangle can be measured directly, and the same triangle will be obtained no matter which pair of magnitudes is used as a basis.

It is desirable to set up a similar type of triangle for a generalized circuit such as an unbalanced polyphase circuit containing non-sine waves of voltage and current. Any definitions made for the generalized circuit should reduce to the corresponding definitions for the simple type of circuit above.

The average power is at our disposal, and we must set up a definition for apparent power, or reactive power, or power factor in order to determine the triangle. There are several matters that should be given some thought before any definition is considered.

1. The generalized definitions will help the engineer very little in designing circuits and machinery and in predicting their performance.

2. The principal use of the generalized definitions will be in adjusting power rates.

3. The definitions must depend only on voltage and current measurements that can be made where the line enters the customer's premises.

4. There is need of postulating a conservation of reactive power law, we may do so if we desire, but there is no natural or physical reason for it since reactive power is a parameter instead of a physical magnitude.

5. The method of fixing the rates by the generalized definitions will be intended to persuade the customer to keep his load balanced, and to keep the harmonics as small as possible. Any summation for reactive power which would let one harmonic effect cancel another obviously is unfair to the power company.

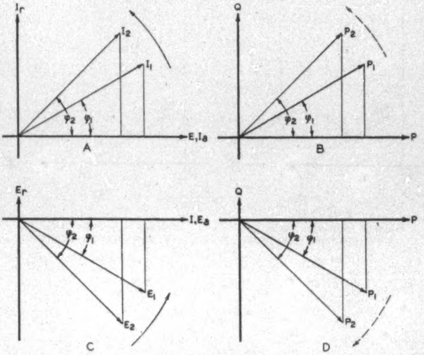


FIG. 13

6. Perhaps if the term penalty factor were introduced to replace the term power factor for the generalized circuit the theoreticians would find a definition based on these considerations more acceptable.

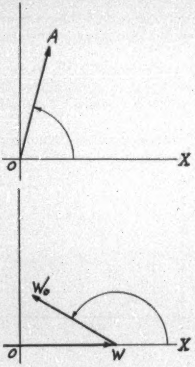
No doubt there are many definitions that can be arrived at which satisfy the requirements set forth above. One set of generalized definitions is given below:

| | | |
|---|---|---|
| Apparent power | $nEI$ | volt-ampere rating |
| Average power | $P$ | average power |
| Power factor | $P/(nEI)$ | penalty factor |
| Reactive power | $\sqrt{(nEI)^2 - P^2}$ | penalty power |

where $n$ is the number of phases, $E$ is the maximum effective voltage from ground to any of the lines, and $I$ is the maximum effective current in any of the lines. There also are listed alternative names for some of the parameters defined.

**J. E. Clem:** This discussion is based on certain fundamental conceptions and it seems expedient to present them so that the discussion will be understood in the way it is intended.

The mathematics used in alternating-current theory is in reality more or less of an experimental nature. That is, certain methods in mathematical manipulations have been found to agree with observed results. It has been observed that the voltage and current in the simple alternating-current circuit vary with time and it has been noted that the best results in operation and calculation are obtained when the variation is made sinusoidal. It has been found also that certain operations can be performed upon the current and voltage according to the rules of vector algebra and the correct result obtained. For instance, the scalar product of two vectors is defined as the product of the vectors times the angle between them and this gives the power in watts. Also the vector product is defined as the product of the vectors times the sine of the angle between them and this gives the reactive power or the quadrature component of the volt-amperes. It has a positive or negative sign depending upon whether the angle between the two vectors is positive or negative as measured from the reference vector. It has also been observed that certain operations can be made according to the rules of complex numbers.

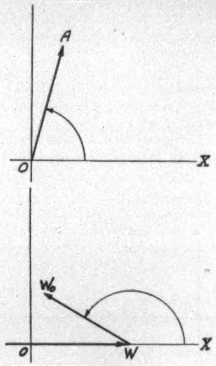


A

FIG. 14A

Current reference (Fig. 18)
Trigonometric symbolism

$$\begin{aligned} OA &= I \\ i &= I \operatorname{Cos} \omega t \\ OA &= I_r = E_r \\ e_r &= E_r \operatorname{Cos} \omega t \\ XOA &= \omega t \\ ie_r &= \frac{IE_r}{2} (1 + \operatorname{Cos} 2\, \omega t) \\ OW &= WW_o = \frac{IE_r}{2} \\ XWW_o &= 2\, \omega t \end{aligned}$$



B

FIG. 14B

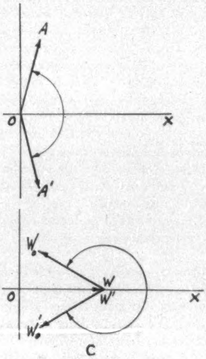
Voltage reference (Fig. 19)
Trigonometric symbolism

$$\begin{aligned} OA &= E \\ e &= E \cos \omega t \\ OA &= E_r = I_r \\ i_r &= I_r \operatorname{Cos} \omega t \\ XOA &= \omega t \\ ei_r &= \frac{EI_r}{2} (1 + \operatorname{Cos} 2\, \omega t) \\ OW &= WW_o = \frac{EI_r}{2} \\ XWW_o &= 2\, \omega t \end{aligned}$$

There is a tendency for many people to consider that the $j$ part is a mathematical expression as an imaginary quantity or, as some are pleased to call it, a mathematical fiction. Such is not the case, since usually there is some physical fact back of most such expressions. For instance, consider an inductive circuit. The drop across the inductance depends upon the rate of change of current in it and the rate of change is maximum 90 deg before or after the current maximum. This 90 deg phase relation can mathematically be expressed by use of the symbol $j$ and $jx$ certainly is not an imaginary quantity but in reality is a quadrature quantity as compared with resistance.

Instantaneous power always is the product of the instantaneous voltage and instantaneous current. It is obvious that the power is a double frequency phenomenon, since for the simple resistance circuit it would be maximum when the current and voltage are maximum in the positive direction and again maximum when they are maximum in the negative direction and since this kind of power has no negative values such a variation calls for a double frequency. It is known that with certain circuits the current maximum does not occur at the time of voltage maximum but occurs 90 deg later or earlier. If there is an inductance in the circuit the voltage across the inductance depends upon the rate of change of the current. In this case also the instantaneous power is the product of the instantaneous values of voltage and current but since the maximum values occur 90 deg apart, the power will be positive or negative depending upon the time position. Since the power will be zero for each current zero and also zero for each voltage zero, there will be four zeros for each complete voltage or current cycle which again requires double frequency. The power taken by such a circuit is a real power and is fed into the inductance for half the power cycle and then is fed from the inductance to the circuit for the other half of the power cycle.

There has been considerable thought expended in an effort to define reactive power and it seems that the best approach to this would be to decide first just exactly what reactive power is. In a purely resistance circuit the product of volts and amperes gives watts. If there is reactance in the circuit in addition to the resistance, the product of volts and amperes gives a quantity larger than the watts. If there is a rectifying device in the circuit there is another difference and in this case the difference between watts and volt-amperes should not be ascribed to reactance or called reactive power. For the single-phase case suitable definitions have been given in Professor Smith's paper. The extension to polyphase circuits requires further study.

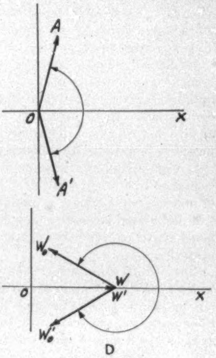


C

FIG. 14C

Current reference (Fig. 18)
Exponential symbolism

$$\begin{aligned} OA &= OA' = \frac{I}{2} \\ i &= \frac{I}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\ OA &= OA' = r\frac{I}{2} = \frac{E_r}{2} \\ e_r &= \frac{E_r}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\ XOA &= \omega t \quad XOA' = -\omega t \\ OW &= OW' = WW_o = W'W_o' \\ &= \frac{IE_r}{4} \\ ie_r &= \frac{IE_r}{4} (1 + \epsilon^{j2\omega t} + 1 \\ &\quad + \epsilon^{-j2\omega t}) \\ XWW_o &= 2\, \omega t \quad XW'W_o' = -2\, \omega t \end{aligned}$$



D

FIG. 14D

Voltage reference (Fig. 19)
Exponential symbolism

$$\begin{aligned} OA &= OA' = \frac{E}{2} \\ e &= \frac{E}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\ OA &= OA' = \frac{E}{2r} = \frac{I_r}{2} \\ i_r &= \frac{I_r}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) \\ XOA &= \omega t \quad XOA' = -\omega t \\ OW &= OW' = WW_o = W'W_o' \\ &= \frac{EI_r}{4} \\ ei_r &= \frac{EI_r}{4} (1 + \epsilon^{j2\omega t} + 1 \\ &\quad + \epsilon^{-j2\omega t}) \\ XWW_o &= 2\, \omega t \quad XW'W_o' = -2\, \omega t \end{aligned}$$

There has also been considerable discussion as to whether the reactive volt-amperes in an inductive circuit should be considered as positive or negative. This is a waste of time because there are enough previously adopted conventions to indicate which sign should be used. Actually the sign depends upon whether the current or voltage is considered as the reference in determining the sign of the angle between the two. If the current is taken as the basis of reference then the angle between the current and voltage is positive and the reactive volt-amperes in an inductive circuit will be positive. If the voltage is taken as the basis of reference then the angle between voltage and current will be negative and the inductive volt-amperes automatically will have a negative sign. This is very well illustrated in the diagrams in Figs. 14-17 in which the current and voltage are represented trigonometrically and exponentially.

Mr. Fortescue limits himself to the use of the current or the reference vector when he sets up an equation (2) which gives the power in an alternating-current circuit and then arbitrarily considers only part of that equation (3) for the rest of his argument. This arbitrary step nullifies much of the subsequent discussion because if he had used voltage as the basis of reference, a different result would have been obtained in (3) as is evident from the preceeding table.

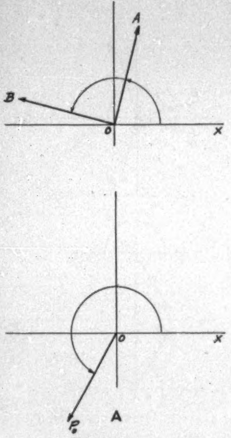


Fig. 15A

Current reference (Fig. 18)
Trigonometric symbolism

$$\begin{aligned}
OA &= I\\
i &= I\ \mathrm{Cos}\ \omega t\\
e_x &= L\frac{di}{dt} = -\omega LI\ \mathrm{Sin}\ \omega t\\
&= E_x\ \mathrm{Cos}\ (\omega t + 90)\\
OB &= E_x\\
XOA &= \omega t \quad XOB = \omega t + 90\\
OP_o &= \frac{IE_x}{2}\\
ie_x &= \frac{IE_x}{2}\ \mathrm{Cos}\ (2\omega t + 90)\\
XOP_o &= 2\,\omega t + 90
\end{aligned}$$

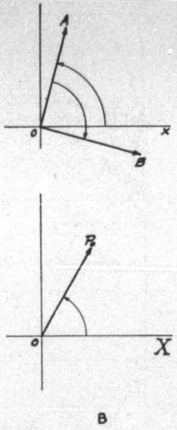
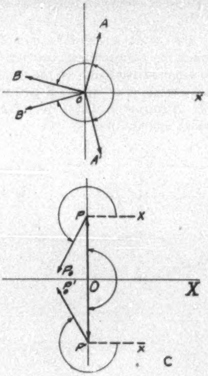


Fig. 15B

Voltage reference (Fig. 19)
Trigonometric symbolism

$$\begin{aligned}
OA &= E\\
e &= E\cos \omega t\\
i_x &= \int \frac{e}{L}\,dt = \frac{E}{\omega L}\ \mathrm{Sin}\ \omega t\\
&= I_x\ \mathrm{Cos}\ (\omega t - 90)\\
OB &= I_x\\
XOA &= \omega t \quad XOB = \omega t - 90\\
OP_o &= \frac{EI_x}{2}\\
ei_x &= \frac{EI_x}{2}\ \mathrm{Cos}\ (2\,\omega t - 90)\\
XOP_o &= 2\,\omega t - 90
\end{aligned}$$

| Current reference | Voltage reference |
|---|---|
| **Direct current** | |
| $e = Ri$ | $i = \frac{E}{r}$ |
| $\omega = Ri^2$ | $\omega = \frac{E^2}{r}$ |
| **Alternating current** | |
| $e_r = ri$ | $i_r = \frac{e}{r}$ |
| $e_x = xi$ | $i_x = \frac{e}{x}$ |
| $e = (r + jx)\,i$ | $i = e\left(\frac{1}{r} - j\frac{1}{x}\right)$ |
| $\omega = ri^2$ | $\omega = \frac{e^2}{r}$ |
| $RVA = xi^2$ | $RVA = \frac{e^2}{x}$ |
| $VA = (r + jx)\,i^2$ | $VA = e^2\left(\frac{1}{r} - j\frac{1}{x}\right)$ |
| $= P + jQ$ | $= P' - jQ'$ |



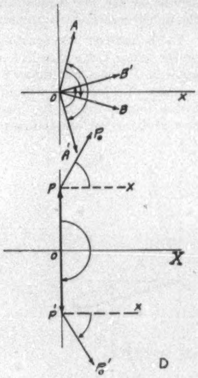


Fig. 15C

Current reference (Fig. 18)—Exponential symbolism

$$\begin{aligned}
OA &= OA' = \frac{I}{2}\\
i &= \frac{I}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right)\\
e_x &= L\frac{di}{dt} = \omega L\frac{I}{2}\left(j\,\epsilon^{j\omega t} - j\,\epsilon^{-j\omega t}\right)\\
&= \frac{E_x}{2}\left(\epsilon^{j(\omega t+90)} + \epsilon^{-j(\omega t+90)}\right)\\
OB &= OB' = \frac{E_x}{2}\\
XOA &= \omega t \quad XOA' = -\omega t\\
XOB &= \omega t + 90 \quad XOB' = -(\omega t + 90)\\
OP &= OP' = PP_o = P'P_o' = \frac{IE_x}{4}\\
ie_x &= \frac{IE_x}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t+90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t+90)}\right)\\
XOP &= 90 \quad XOP' = -90\\
xPP_o &= 2\,\omega t + 90 \quad xP'P_o' = -(2\,\omega t + 90)
\end{aligned}$$

Fig. 15D

Voltage reference (Fig. 19)—Trigonometric symbolism

$$\begin{aligned}
OA &= OA' = E\\
e &= \frac{E}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right)\\
i_x &= \int \frac{e}{L}\,dt = \frac{E}{2\omega L}\left(\frac{\epsilon^{j\omega t}}{j} + \frac{\epsilon^{-j\omega t}}{-j}\right)\\
&= \frac{I_x}{2}\left(\epsilon^{j(\omega t-90)} + \epsilon^{-j(\omega t-90)}\right)\\
OB &= OB' = \frac{I_x}{2}\\
OP &= OP' = PP_o = P'P_o' = \frac{EI_x}{4}\\
ei_x &= \frac{EI_x}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t-90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t-90)}\right)\\
XOP &= 90 \quad XOP' = -90\\
xPP_o &= 2\,\omega t - 90 \quad xP'P_o' = -(2\,\omega t - 90)
\end{aligned}$$

In this table the argument presented by Mr. Fortescue in his equation (3) or Table III is completed and also extended for the case where the voltage is the basis of reference.

It is illuminating to apply the energy storage argument to a parallel circuit of resistance and inductance such as the $r$ and $L$ part of Fig. 19. Obviously the energy dissipation in the resistance occurs when the current in and the voltage across the resistance are at their maximum values. Now the current in the inductance lags 90 deg in respect to the voltage and since the maximum rate of energy inflow to the inductance leads the current by 90 deg, it is in phase coincidence with the maximum rate of energy dissipation in the resistance. Therefore, it is obvious that the stored energy in the reactive part of the circuit as used by Mr. Fortescue is an unsound criterion for determining the sign of reactive volt-ampere.

**V. G. Smith:** In suggesting $P/\sqrt{P^2 + P_r{}^2}$ as the definition of power factor the writer had in mind the approximate measurement of $P_r$ by a wattmeter as is usual at present. If the suggestions of Messrs. Herskind and Smith were adopted power factor would become a "blanket" definition covering reactive power, distortion, unbalance and mesh distribution.

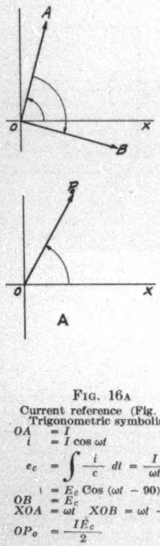


FIG. 16A

Current reference (Fig. 18)
Trigonometric symbolism

$$OA = I$$
$$i = I \cos \omega t$$
$$e_c = \int \frac{i}{c}\, dt = \frac{I}{\omega t} \operatorname{Sin} \omega t$$
$$= E_c \operatorname{Cos} (\omega t - 90)$$
$$OB = E_c$$
$$XOA = \omega t \quad XOB = \omega t - 90$$
$$OP_o = \frac{IE_c}{2}$$
$$ie_c = \frac{IE_c}{2} \operatorname{Cos} (2\,\omega t - 90)$$
$$XOP = 2\,\omega t - 90$$

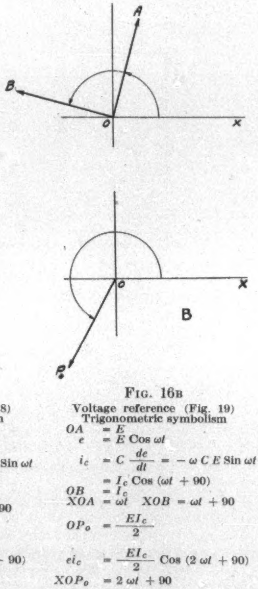


FIG. 16B

Voltage reference (Fig. 19)
Trigonometric symbolism

$$OA = E$$
$$e = E \operatorname{Cos} \omega t$$
$$i_c = C \frac{de}{dt} = -\omega\, C\, E \operatorname{Sin} \omega t$$
$$= I_c \operatorname{Cos} (\omega t + 90)$$
$$OB = I_c$$
$$XOA = \omega t \quad XOB = \omega t + 90$$
$$OP_o = \frac{EI_c}{2}$$
$$ei_c = \frac{EI_c}{2} \operatorname{Cos} (2\,\omega t + 90)$$
$$XOP_o = 2\,\omega t + 90$$

These four things cost differently, distortion goes back to the generators with little chance of correction, reactive power may be generated locally by condensers, and unbalance and mesh distribution may be corrected by a judicious arrangement of customers' loads. It seems then that the one factor is insufficient to cover such a diversity of conditions.

Professor Karapetoff certainly is correct when he asserts that the complete physical information about a circuit is given only by the instantaneous currents and voltages. But, given a perfect set of oscillograms, one would be in the position of a statistician with a mass of data, complete but incomprehensible until a few significant quantities have been extracted. This is one reason why these quantities and factors are worth defining.

**C. L. Fortescue:** This closing discussion is confined to the much discussed question of the appropriate sign for reactive power as expressed in vector notation. In other words shall we use $E$ conjugate $I$ or $I$ conjugate $E$. It is not a question of which is right because, as the writer has pointed out many times before

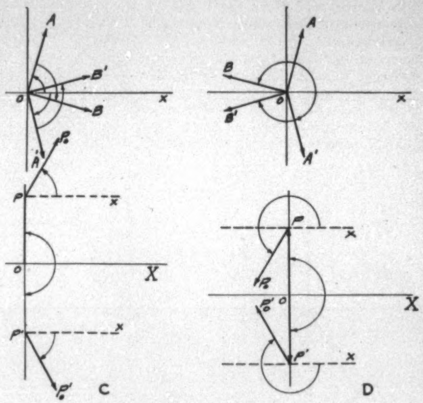


FIG. 16C

Current reference (Fig. 18)—Exponential symbolism

$$OA = OA' = \frac{I}{2}$$
$$i = \frac{I}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$e_c = \int \frac{i}{c}\, dt = \frac{I}{2\omega c} \left( \frac{\epsilon^{j\omega t}}{j} + \frac{\epsilon^{-j\omega t}}{-j} \right)$$
$$= \frac{E_c}{2} (\epsilon^{j(\omega t - 90)} + \epsilon^{-j(\omega t - 90)})$$
$$OB = OB' = \frac{E_c}{2}$$
$$XOA = \omega t \quad XOA' = -\omega t$$
$$XOB = \omega t - 90 \quad XOB' = -(\omega t - 90)$$
$$OP = OP' = PP_o = P'P_o' = \frac{IE_c}{4}$$
$$ie_c = \frac{IE_c}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t - 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t - 90)})$$
$$XOP = 90 \quad XOP' = -90$$
$$xPP_o = 2\,\omega t - 90 \quad xP'P_o' = -(2\,\omega t - 90)$$

FIG. 16D

Voltage reference (Fig. 19)—Exponential symbolism

$$OA = OA' = \frac{E}{2}$$
$$e = \frac{E}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$i_c = C \frac{de}{dt} = \omega\, C \frac{E}{2} (j\, \epsilon^{j\omega t} - j\, \epsilon^{-j\omega t})$$
$$= \frac{I_c}{2} (\epsilon^{j(\omega t + 90)} + \epsilon^{-j(\omega t + 90)})$$
$$OB = OB' = \frac{I_c}{2}$$
$$XOA = \omega t \quad XOA' = -\omega t$$
$$XOB = \omega t + 90 \quad XOB' = -(\omega t + 90)$$
$$OP = OP' = PP_o + P'P_o' = \frac{EI_c}{4}$$
$$ei_c = \frac{EI_c}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t + 90)} + \epsilon^{-j90} + j^{-(2\omega t + 90)})$$
$$XOP = 90 \quad XOP' = -90$$
$$xPP_o = 2\,\omega t + 90 \quad xP'P_o' = -(2\,\omega t + 90)$$

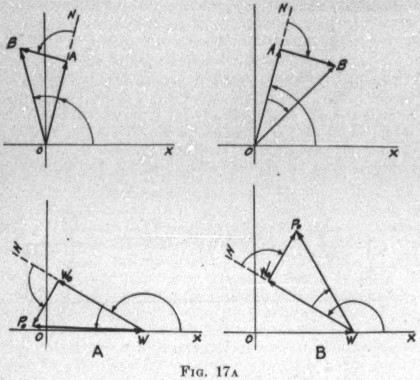


Fig. 17A

Current reference (Fig. 18) Trigonometric symbolism

$$OA = I \qquad i = I \text{ Cos } \omega t$$
$$OA = E_r = rI$$
$$AB = E_x = xI$$
$$OB = OA + AB = E$$
$$XOA = \omega t \qquad NAB = 90$$
$$AOB = \theta \qquad \text{Tan } \theta = \frac{x}{r}$$
$$XOB = \omega t + \theta$$
$$e = E \text{ Cos } (\omega t + \theta)$$
$$OW = WW_o = \frac{IE_r}{2} = \frac{IE}{2} \text{ Cos } \theta$$
$$W_oP_o = \frac{IE_x}{2} = \frac{IE}{2} \text{ Sin } \theta$$
$$WP_o = \frac{IE}{2}$$
$$ie = \frac{IE}{2} \left\{ \text{Cos } \theta\, (1 + \text{Cos } 2\,\omega t) + \text{Sin } \theta \text{ Cos } (2\,\omega t + 90) \right\}$$
$$= \frac{IE}{2} \left\{ \text{Cos } \theta + \text{Cos } (2\,\omega t + \theta) \right\}$$
$$XWW_o = 2\,\omega t \qquad XWP_o = 2\,\omega t + \theta$$
$$X\overline{WW_o}P_o = 2\,\omega t + 90$$

Fig. 17B

Voltage reference (Fig. 19)—Trigonometric symbolism

$$OA = E \qquad e = E \text{ Cos } \omega t$$
$$OA = I_r = \frac{E}{r}$$
$$AB = I_x = \frac{E}{x}$$
$$OB = OA + AB = I$$
$$XOA = \omega t \qquad NAB = -90$$
$$AOB = \theta \qquad \text{Tan } \theta = \frac{x}{r}$$
$$XOB = \omega t - \theta$$
$$i = I \text{ Cos } (\omega t - \theta)$$
$$OW = WW_o = \frac{EI_r}{2} = \frac{EI}{2} \text{ Cos } \theta$$
$$W_oP_o = \frac{EI_x}{2} = \frac{EI}{2} \text{ Sin } \theta$$
$$WP_o = \frac{IE}{2}$$
$$ei = \frac{EI}{2} \left\{ \text{Cos } \theta\, (1 + \text{Cos } 2\,\omega t + \text{Sin } \theta \text{ Cos } (2\,\omega t - 90) \right\}$$
$$= \frac{EI}{2} \left\{ \text{Cos } \theta + \text{Cos } (2\,\omega t - \theta) \right\}$$
$$XWW_o = 2\,\omega t \qquad XWP_o = 2\,\omega t - 90$$
$$X\overline{WW_o}P_o = 2\,\omega t - 90$$

they are both equally valid, but the first has the sanction of priority and common usage. Unfortunately, many recent text book writers have adopted the second definition because they thought it was more consistent with the emf and current vector diagram.

In the dynamic theory of currents 2 kinds of forces are recognized, besides those arbitrarily imposed on the system, namely conservative and nonconservative. In linear circuits the nonconservative forces are directly proportional to the velocities or currents while the conservative forces are proportional to the displacements (changes) or to the accelerations (rate of change of currents). In the Lagrangian equations of the system and the same equation obtained by the application of Kirchoff and Lenz laws, the impressed emfs are equilibrated by these forces, and the set of equations so obtained completely specify the electrical system.

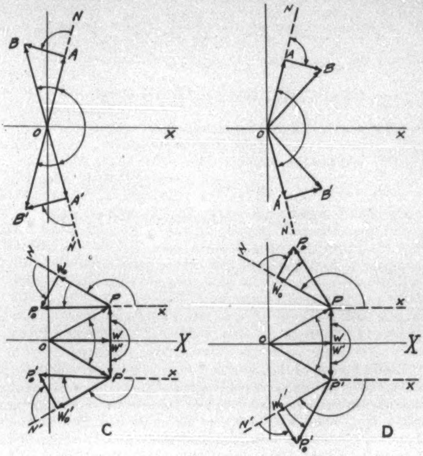


Fig. 17C

Current reference (Fig. 18)—Exponential symbolism

$$OA = OA' = \frac{I}{2} \qquad i = \frac{I}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t})$$
$$OA = OA' = \frac{E_r}{2} = r\,\frac{I}{2}$$
$$AB = A'B' = \frac{E_x}{2} = x\,\frac{I}{2}$$
$$OB = OB' = OA + AB = OA' + A'B' = \frac{E}{2}$$
$$XOA = \omega t \qquad XOA' = -\,\omega t$$
$$AOB = \theta \qquad A'OB' = -\,\theta$$
$$\text{Tan } \theta = \frac{x}{r}$$
$$NAB = 90 \qquad N'A'B' = -\,90$$
$$e = \frac{E_r}{2} (\epsilon^{j\omega t} + \epsilon^{-j\omega t}) + \frac{E_x}{2} (\epsilon^{j(\omega t + 90)} + \epsilon^{-j(\omega t + 90)})$$
$$= \frac{E}{2} (\epsilon^{j(\omega t + \theta)} + \epsilon^{-j(\omega t + \theta)})$$
$$OW = OW' = PW_o = P'W_o' = \frac{IE_r}{4}$$
$$WP = W'P' = W_oP_o = W_o'P_o' = \frac{IE_x}{4}$$
$$OP = OP' = PP_o = P'P_o' = \frac{IE}{4}$$
$$ie = \frac{IE_r}{4} (1 + \epsilon^{j2\omega t} + 1 + \epsilon^{-j2\omega t})$$
$$+ \frac{IE_x}{4} (\epsilon^{j90} + \epsilon^{j(2\omega t + 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t + 90)})$$
$$= \frac{IE}{4} (\epsilon^{j\theta} + \epsilon^{j(2\omega t + \theta)} + \epsilon^{-j\theta} + \epsilon^{-j(2\omega t + \theta)})$$
$$XWP = 90 \qquad XW'P = -\,90 \qquad WOP = \theta$$
$$W'OP' = -\,\theta \qquad xPW_o = 2\,\omega t \qquad xP'W_o' = -\,2\,\omega t$$
$$x\overline{PW_o}P_o = 2\,\omega t + 90 \qquad x\overline{P'W_o'}P_o' = -(2\,\omega t + 90) \qquad W_oPP_o = \theta$$
$$W_o'PP_o' = -\,\theta \qquad xPP_o = 2\,\omega t + \theta \qquad xP'P_o' = -\,(2\,\omega t + \theta)$$

FIG. 17D

**Voltage reference (Fig. 19)—Exponential symbolism**

$$OA = OA' = \frac{E}{2} \qquad e = \frac{E}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right)$$

$$OA = OA' = \frac{I_r}{2} = \frac{E}{2r}$$

$$AB = A'B' = \frac{I_x}{2} = \frac{E}{2x}$$

$$OB = OB' = OA + AB = OA' + A'B' = \frac{I}{2}$$

$$\begin{aligned} XOA &= \omega t & \qquad XOA' &= -\omega t \\ AOB &= \theta & A'OB &= -\theta \end{aligned}$$

$$\text{Tan}\,\theta = \frac{x}{r}$$

$$NAB = -90 \qquad N'A'B' = 90$$

$$i = \frac{I_r}{2}\left(\epsilon^{j\omega t} + \epsilon^{-j\omega t}\right) + \frac{I_x}{2}\left(\epsilon^{j(\omega t - 90)} + \epsilon^{-j(\omega t - 90)}\right)$$

$$= \frac{I}{2}\left(\epsilon^{j(\omega t - 90)} + \epsilon^{-j(\omega t - 90)}\right)$$

$$OW = OW' = PW_o = P'W_o' = \frac{EI_r}{4}$$

$$WP = W'P' = W_oP_o = W_o'P_o' = \frac{EI_x}{4}$$

$$OP = OP' = PP_o = P'P_o' = \frac{EI}{4}$$

$$ei = \frac{EI_r}{4}\left(1 + \epsilon^{j(2\omega t - 90)} + 1 + \epsilon^{-j(2\omega t - 90)}\right)$$

$$+ \frac{EI_x}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t - 90)} + \epsilon^{-j90} + \epsilon^{-j(2\omega t - 90)}\right)$$

$$= \frac{EI}{4}\left(\epsilon^{j90} + \epsilon^{j(2\omega t - 90)} + \epsilon^{-j90} + \epsilon^{-j(\omega t - 90)}\right)$$

$$\begin{aligned} XWP &= 90 & \qquad XW'P' &= -90 \\ WOP &= \theta & W'OP' &= -\theta \\ xPW_o &= 2\,\omega t & xP'W_o' &= -2\,\omega t \\ x\overline{PW_o}P_o &= 2\,\omega t - \theta & x\overline{P'W_o'}P_o' &= -(2\,\omega t - \theta) \\ W_oPP_o &= -\theta & W_o'P'P_o' &= \theta \\ xPP_o &= 2\,\omega t - \theta & xP'P_o' &= -(2\,\omega t - \theta) \end{aligned}$$

Each equation of the set of equations so obtained represents a series circuit having the characteristics of the simple series circuits discussed in the paper and therefore the arguments given in that paper apply with equal force to the more general systems of equation comprising both positional and motional conservative forces as well as nonconservative or dissipative forces. The operational solution of these Lagrangian equations gives the reciprocal system of equations in which the velocities or currents are given in terms of the impressed emfs but these equations cannot be considered as fundamental, since we cannot define conservative and nonconservative motions. In other words, these equations cannot be derived from Hamilton's principle without the intermediate step of obtaining the Lagrangian equations of motion or what is the same thing, the equivalent equation obtained by Kirchoff and Lenz laws.

These equations when dealing with harmonic impressed emfs may be expressed in equivalent vector form. Thus the Lagrangian equations for the simple circuit that is shown in Fig. 20 are:

$$\left.\begin{aligned} e &= r_1 i_1 + L_1 \frac{di_1}{dt} \\ e &= r_2 i_2 \end{aligned}\right\} \qquad (1)$$

These equations may be expressed in vector form in either of the two forms

$$\left.\begin{aligned} \check{E} &= (r_1 + jx_1)\,\check{I}_1 \\ \check{E} &= r_2 \check{I}_2 \end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned} \hat{E} &= (r_1 - jx_1)\hat{I}_1 \\ \hat{E} &= r_2 \hat{I}_2 \end{aligned}\right\} \qquad (2a)$$

Equation (2) being in terms of positively rotating vectors and (2a) being in terms of negatively rotating vectors and $x_1$ in each case being equal to $2\pi f L_1$ where $f$ is the frequency

From (2) we have

$$\left.\begin{aligned} \check{E}\hat{I}_1 = P_1 + jQ_1 &= (r_1 + jx_1)\,I_1^2 \\ \check{E}\hat{I}_2 = P_2 \qquad &= I_2^2 r_2 \\ P_1 + P_2 + jQ_1 &= r_1 I_1^2 + r_2 I_2^2 + jx_1 I_1^2 \end{aligned}\right\} \qquad (3)$$

From (2) we have

$$\left.\begin{aligned} \hat{E}I_1 = P_1 - jQ_1 &= (r_1 - jx_1)\,I_1^2 \\ \hat{E}I_2 = P_2 \qquad & \\ P_1 + P_2 - jQ_1 &= r_1 I_1^2 + r_2 I_2^2 + jx_1 I_1^2 \end{aligned}\right\} \qquad (3a)$$

Definition (3) is associated with a system of positively rotating vectors, whereas (3a) is associated with a system of negatively rotating vectors. These vectors $\check{I}_1 \check{I}_2\, \hat{I}_1 \hat{I}_2$ are derived vectors and should not be used to determine the direction of $Q_1$. Equations (2) and (3) should give a satisfactory answer to Mr. Clem's criticisms since his multiple circuit and for that matter, any multiple circuit is simply a number of series circuits each of which fulfills the criterion set up in the paper. The total power is obtained by the sum of the powers in the individual circuits and the total reactive volt-amperes is the sum of the reactive volt-amperes of each individual series circuit.

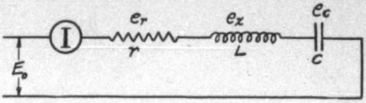


FIG. 18

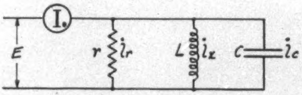


FIG. 19

Referring now to Mr. Alger's discussion, he says "in dealing with constant current systems, it is the general practice to use equation (2)" of his discussion. This may be the recognized practice with constant current systems, but it is also the *general* practice with constant potential systems. In a complex network the self and mutual admittances are derived constants into which many of self and mutual impedances enter. These latter constants of the system are derived from the resistances, the coefficients of self and mutual induction and the coefficients of potential and these are the fundamental constants of any electrical system. The fundamental equations of a linear electrical constant potential system are therefore of the form defined by his equation (2). The admittance equations are the reciprocal or derived equations. Both systems of equation are useful in technical work.

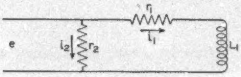


FIG. 20

Contrary to the opinion implied in Mr. Alger's discussion the use of the term "lagging power-factor generator" for an over-excited generator is completely in accord with the definition

$$\check{E}\hat{I} = P + jQ$$

This is expressed in the old conventional diagram shown in Fig. 21. There it is plain that the true power lags behind the apparent power, so there is no inconsistency in the diagram. Such a generator delivers *positive* reactive volt-amperes to the system. Similarly, a synchronous condenser might aptly be termed a reactive power generator, for when it is overexcited it delivers *positive* reactive power to the system and when underexcited it receives *positive* reactive power from this system or delivers *negative* reactive power to the system.

It is hardly necessary to point out that in the Lagrangian system of equation for linear circuits each impressed force may be considered independently of all the others so that when harmonics are present there are as many power factors as there are harmonics. Similarly an inphase system with grounded neutral requires $n + 1$ equation to define it for sinusoidal impressed emfs so that it requires as many factors to completely specify it under unbalanced conditions.

**J. Allen Johnson:** It is apparent from the discussions by Messrs. Sanderson and Corney, that operating men are in general agreement with the philosophy and practice presented in the writer's paper. From this point of view, there seems to be no disagreement and hence no rebuttal is necessary. However, the papers and discussions seem to indicate considerable uncertainty as to the facts regarding reactive power and the relation of these facts to the conventions established or to be established in regard to it. It therefore may be of some service in resolving and clarifying these questions for an engineer with the operating point of view to make an attempt to analyze the facts and relate them to the conventions.

1. Let us start by recalling one or two fundamental concepts and defining the terms we must use.

A. It is energy that flows, not power. Power is the rate of flow or conversion of energy.

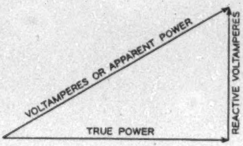


FIG. 21

B. There are two concepts of "active power" which may be named and defined as follows:

(1) *Real active power* is the rate of flow (or change of *form*) of that part of the energy which is being converted into some other form, such as heat, mechanical work or radiation.

(2) *Apparent active power* is the apparent rate of flow of active energy which results from the assumption that the active power is "in phase" with either the total current (pure series circuit) or with the total voltage (pure shunt circuit), the term "in phase" in this sense meaning coincidence of maximum values. The average value of the "apparent active power" is the same as that of the "real active power" although their instantaneous values may differ. This average value $EI \cos \theta$ is the value most commonly referred to.

C. There are 3 concepts of "reactive power" which may be named and defined as follows:

(1) *Real reactive power* is the actual rate of flow (or of change of *state*) of that part of the energy (reactive) which is undergoing cyclic change of state from dynamic to static and *vice versa*.

(2) *Apparent reactive power* is the apparent rate of flow of reactive energy resulting from the assumption that the active power is "in phase" with either the total current (pure series circuit) or the total voltage (pure shunt circuit), the term "in phase" in this sense meaning coincidence of maximum values. One or the other of these assumptions is tacitly made whenever the current or voltage vector is used as a reference. The average value of "reactive power" is zero.

(3) *Fictitious reactive power* is the reading of a correctly connected reactive kva meter. It is the average value of a harmonic having an amplitude equal to that of the "apparent" reactive power but with its neutral position displaced from zero by an amount equal to the maximum amplitude of the "apparent" reactive power wave. The name "var" has been adopted as the unit of this fictitious power.

D. "Real" and "apparent" power, both active and reactive, can be thought of in two ways namely:

(1) With respect to the point or plane of measurement, as rate of energy flow.

(2) With respect to the circuit measured, as a rate of energy conversion.

2. There are several questions that require answers for the clear understanding of reactive power, *viz.:*

A. Are there any such things as "real" active and reactive power?

B. When current lags does reactive power also lag and if so what does it lag?

C. What are the relationships between the several kinds of active and reactive power above defined?

D. Which of the above kinds of reactive power is it, the sign of which is under discussion?

E. What is the physical meaning of this sign?

3. As to question (A), Mr. Wright's discussion would seem to settle this question in the affirmative. Simultaneous instantaneous values of $(e)$ and $(i)$ are real, hence their product must be real. Similarly instantaneous values of $(i^2)$ times $(R)$ are real. Both of these measure instantaneous values of power in watts. Their arithmetic difference then cannot be other than watts, and if this arithmetic difference can be identified with the "reactive power" then the reactive power must be real and expressible in watts. This identity has been established, which proves that energy transformations of the nature defined do take place. The magnitudes and time phase of the real reactive power do not usually coincide with those of the "apparent" reactive power unless the "real" active power cycle actually is "in phase" with either the voltage or the current.

4. Question (B) also will be answered by further reference to Mr. Wright's discussion.

It will be observed that, in the simple series circuit he has assumed, the active power, $i^2r$, is "in phase" with the total current (in the sense that its maximum values are simultaneous with those of the current). The maximum values of the reactive power, in this case *lead* those of the active power by 90 deg in the double frequency power cycle. However, had Mr. Wright assumed a simple shunt circuit in which the resistance and reactance were in parallel, the voltage and total current remaining the same and in the same phase relation, then the active power component of the total power would have been "in phase" with the total *voltage* instead of with the total current. The curve of instantaneous total power would have been the same as before and the reactive power wave would have *lagged* 90 deg behind the alternating component of the "active" power wave. It may thus be deduced, that in a complex circuit involving combinations of series and parallel inductive impedances the alternating component of the "real active power" wave may be "in phase" with neither the voltage nor the current, and the real *inductive reactive power wave either may lead or lag the alternating component of the active power* (in the double frequency cycle) by 90 deg.

Thus we are forced to the conclusion that, while in any specific case there is a "real" active power wave at double system frequency and a "real" corresponding reactive power wave, there is no way of determining, from measurements of the total current, voltage and power, either by rms instruments or by oscillographs, what the instantaneous magnitudes and phase relationship of these "real" waves are, either with respect to the current and voltage or with respect to each other. That is to say, so far as the point of measurement is concerned, the only "realities" are the instantaneous voltage, current and total power and their rates of change. What is meant by "reality" in reference to active and reactive power refers to the instantaneous rates at which energy is being "actively" and "reactively" converted in the circuit being measured.

5. The relationships of question (C) perhaps will become clear if we write the complete expression for instantaneous total power using any reference $\omega t = o$ such that the angle between $E$ and the reference is $\alpha$ and the angle between $I$ and the reference is $(\theta + \alpha)$. Then we have:

$e = E_m \cos(\omega t - \alpha)$, the instantaneous value of voltage.

$i = I_m \cos(\omega t - (\theta + \alpha))$, the instantaneous value of current.

whence, after expanding and substituting rms values we have:

$$ei = EI[(\cos\theta + \cos(2\alpha + \theta)\cos 2\omega t) + (\sin(2\alpha + \theta)\sin 2\omega t)]$$

if $\alpha = 0$ (which assumes active power "*in phase*" *with voltage*) we have:

$$\begin{aligned} ei &= EI[(\cos\theta + \cos\theta\cos 2\omega t) + (\sin\theta\sin 2\omega t)] \\ &= P + P\cos 2\omega t + Q\sin 2\omega t \end{aligned}$$

if $\alpha = -\theta$ (which assumes active power *in phase with current*) we have:

$$\begin{aligned} ei &= EI[(\cos\theta + \cos\theta\cos 2\omega t) - (\sin\theta\sin 2\omega t)] \\ &= P + P\cos 2\omega t - Q\sin 2\omega t \end{aligned}$$

for most other values of $\alpha$ the coefficients of $(\cos 2\omega t)$ and $(\sin 2\omega t)$ will have values other than $P$ and $Q$ respectively.

The first 2 terms of the above equation involving $(EI \cos\theta)$ represent the "apparent active power" and the last term involving $(EI \sin\theta)$ the "apparent reactive power." It will be noted that *the active power is the sum of a constant and a harmonic variable.* When either current or voltage is used as reference the amplitude of the harmonic is equal to the constant, but this relationship does not hold for the general case. The reactive power contains no constant term.

It thus appears that when we use either the current or the voltage vector as a reference, we are simply *making an entirely arbitrary assumption* that the active power is "in phase" respectively with either the current or the voltage. The actual "reality" may be either the current or the voltage or neither. One of these arbitrary assumptions makes the resulting "apparent" inductive reactive power negative, the other positive. The "real" reactive power may either be positive or negative with respect to the active power, but we cannot tell which.

We can however, by making either of these arbitrary assumptions determine certain values, *viz.:*

A. The average value $(EI \cos\theta)$ of the total power.

B. The average value $(EI \cos\theta)$ of active power (both "apparent" and "real") since this is the same as the average value of the total power.

C. The maximum amplitude $(EI \cos\theta)$ of the alternating component of apparent "active power."

D. The maximum amplitude $(EI)$ of the alternating component of the total power. This is equal to the so-called "apparent power" or "total volt-amperes."

E. The average value $(EI \sin\theta)$ of the "fictitious" reactive power. This is the quantity registered by a reactive kva meter.

F. The maximum amplitude $(EI \sin\theta)$ of the "apparent" reactive power wave. The average value of this wave is zero.

In order to clear up this whole subject it seems necessary to correct what seems to be a slight misconception contained in Mr. Alger's discussion. Mr. Alger says

> "Active power flows continuously in the same direction in each conductor of the system, while reactive power flow alternates in direction in each conductor at double line frequency. The combination of active and reactive power is, therefore, exactly analogous to that of the direct and alternating components of a pulsating unidirectional current. In each case the two quantities have different frequencies, and so cannot properly be represented by vectors in a common time diagram. No physical reality can be ascribed to the angles in a right-angled triangle representing the a-c and d-c components of a pulsating current."

In the case of the active power, the expression "flows continuously" is true only in the sense that the flow of active energy does not reverse in direction. The active power does however, pulsate at double frequency between the values of $o$ and $2P$, where $P$ is its average value. It is the average value, $P$, which we think of as measuring the rate at which energy is "flowing continuously" but this value has no physical instantaneous reality except twice in each cycle.

As a matter of fact the active power alone and of itself contains both a constant and an alternating term as above pointed out and hence corresponds to a combination of a direct and alternating current.

Obviously there is no angle involved between the constant term $P$ and the harmonic $Q \sin 2\omega t$. However, there is a definite angle between $P \cos 2\omega t$ and $Q \sin 2\omega t$ which are both double frequency harmonic functions.

Where $P$ and $Q$ are used as the sides of a right angled triangle, it is the $(P)$ appearing in the second term of the above equation, *not the constant* term $(P)$ which is used. The resultant of $\overline{P} + \overline{Q}$ is the total volt-amperes $EI$ which is the maximum value of the alternating component of the total power, that is of $EI \cos\theta \cos 2\omega t \pm EI \sin\theta \sin 2\omega t$.

6. From the above discussion there emerge some rather definite conclusions, namely:

A. Active and reactive power are *physical realities*, but the phase relations between these physical realities and the measured pressure and current at any point in a circuit or between each other cannot be determined from these measurements. "Real" inductive reactive power either may lead or lag the "real" active power.

B. The *average values* of active and "fictitious" reactive power can be determined by *arbitrarily choosing a reference vector* to which the measured current and voltage of the circuit may be referred.

C. For *most convenient* mathematical treatment either *the current vector or the voltage vector can be chosen* as the reference vector. This choice is entirely arbitrary and whichever is most convenient in the particular case can be chosen.

D. *Instantaneous* values of "apparent," active, and reactive power *resulting from such arbitrary choice* of a reference vector usually do not correspond to *physical reality*. The actual physical values may lead or lag the "apparent" values by any time phase angle whatever, and may differ from them in amplitude.

E. The resulting algebraic sign of the "apparent" reactive power entirely is a function of recognized conventions and the *arbitrary choice* of a reference vector.

F. "Real" reactive power either may lead or lag the "real" active power, and the "apparent" reactive power either may lead or lag the "apparent" active power depending upon an arbitrary choice. That is, *inductive reactive* power may, both as a physical fact and as a mathematical appearance either lead or lag the active power.

7. The measurement of the total power $P = EI \cos\theta$, is a relatively simple matter, since the thing we measure is the average value of $P + P \cos 2\omega t \pm Q \sin 2\omega t$. Since the average value of the last two terms is zero the instrument reads only $(P)$ the constant term. The reactive power, alone, $EI \sin\theta \sin 2\omega t$ however, having an average value of zero, is more difficult to measure. It is necessary to produce a *fictitious* voltage, in quadrature with the actual voltage, thus giving us a fictitious cosine function, $EI \cos(90\text{ deg} - \theta)$, which we can measure with the same kind of a device we use to measure the value of $EI \cos\theta$. The quantity we actually measure is the average value of $EI \cos(90\text{ deg} - \theta) + EI \cos(90\text{ deg} - \theta)\cos 2\omega t \pm EI \sin(90\text{ deg} - \theta)\sin 2\omega t$. This has the same numerical

value as the maximum amplitude of the harmonic function represented by $EI \sin \theta \sin 2\omega t$, the "apparent" reactive power.

However, this $Q = EI \cos (90 \text{ deg} - \theta)$, although fictitious, is a useful conception, and its measurement a useful accomplishment, because the direction of its apparent flow with reference to the circuit depends upon whether the current lags or leads the voltage, that is, when the current lags behind the voltage the apparent direction of flow of ($Q$) is positive, and when the current leads, the corresponding apparent flow of ($Q$) is negative. Thus an indication of the magnitude and apparent direction of flow of ($Q$) gives us a guide for the *control of* the magnitude and *direction of angular displacement* of the *reactive current*.

Now, having discovered this fictitious entity ($Q$) and having found a use for it, and a method of controlling it, the question apparently arose as to what to call it. Our foreign friends apparently answered this question by calling it "var." The instantaneous values of "real" and "apparent" reactive power, however, are still watts. If this distinction is recognized we can wholeheartedly adopt the name "var" for the fictitious entity, keeping the name "reactive watt" to designate the rate of transfer of reactive energy, whenever we have to refer to this phenomenon. We can then blithely and happily proceed to dispatch our "kilowatts" and "kilovars" forgetting all about "active" and "reactive" realities. The writer is inclined to think that this is the answer from the operating standpoint. However, perhaps we should not call kilovars reactive *power*. In the paper, the writer spoke of "reactive kilowatts," having in mind the actual transfer of reactive energy. Now while the arithmetic value of the fictitious entity ($Q$) which we measure as $EI \cos (90 \text{ deg} - \theta)$ is the same as that of the maximum amplitude of $EI \sin \theta \sin 2\omega t$ the two entities are not the same. One represents a physical reality, whose average value is *0*, the other is a fictitious unreality, whose average value is ($Q$). The perception of this distinction seems necessary for unreserved psychological acceptance of the name "var."

8. In order to answer questions (D) and (E) as to the "sign" of reactive power, it would seem that the first essential should be to define clearly which reactive power is referred to.

1. Is it the "real" reactive power, that is, the rate of conversion of reactive energy $\left(\frac{de}{dt}\right)$ in kilowatts?

2. Is it the "apparent" reactive power ($EI \sin \theta \sin 2\omega t$) in kilowatts?

3. Is it the "fictitious" reactive power, $Q$, that is, the average value of ($i$) times ( ($e$) 90 deg earlier or later) in kilovars?

All 3 of these entities have been referred to as "reactive power."

The second essential would seem to be to define which "sign" is meant, sign ($_1$) referring to direction of flow or sign ($_2$) referring to angular displacement. If it is the real or apparent reactive kilowatts which are concerned then sign ($_2$) must be meant since reactive kilowatts have no average direction of flow. If it is the "kilovars" which are involved, then sign ($_1$) referring to the apparent direction of flow of the average value of the fictitious entity ($Q$) must be meant.

If the writer's understanding is correct the latter is the case. In that event it would appear that the kilovars should be considered positive when they appear to flow in the same direction as the kilowatts (active) (which from the operating standpoint is the case when the current lags the voltage) and negative when they appear to flow in the direction opposite to that of the kilowatts, (which is the case when the current leads the voltage).

Whether or not these suggestions are consistent with the existing conventions and the mathematics they appear to the writer to be in accord with logic and common sense. It certainly is not common sense to have the positive kilovar output of a generator appear to *decrease* when its field current is *increased* but this is exactly what occurs if kilovars are considered negative when current lags, and meters are connected accordingly, following the usual right (+) and left (−) conventions.

The above discussion may be of assistance in resolving some of the confusion that seems to exist as to the physical facts relating to reactive power. It would seem that if these facts can clearly be perceived and understood then the matter of the "sign" should pretty well settle itself.

The writer wishes to acknowledge the assistance of Mr. S. H. Wright in preparing this discussion.

# Testing of High Speed Distance Relays

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**Synopsis.**—*This paper describes the various test methods which have been evolved during three years by The Tennessee Electric Power Company, which pioneered the use of reactance type distance relays in this country. Specific examples with diagrams are given.*

*New considerations brought about by the use of high speed distance relays are discussed, including their adaptability to being tested by means of short circuit tests. General notes and recommendations covering short circuit tests arising from eight years' experience in making them are given together with typical examples.*

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ADEQUATE testing of high speed distance relays is as necessary as the adequate inspection and maintenance of any other electrical equipment. The type and frequency of testing will vary with the nature or purpose of the test. Relay tests may be classified as follows: (1) acceptance; (2) installation; (3) periodic; (4) surveillance; and (5) development.

Acceptance tests are made to check each individual shipment of relays as received from the manufacturer. Such tests are usually made in the power company's laboratory, and serve to determine whether the relays are in good condition and whether they meet the customer's purchase specifications (if any) and the manufacturer's guarantees.

Installation tests are usually made in the field after the relays have been mounted and wired and are ready for service. These tests check the design and construction of the complete protective scheme. Similar tests are also made after any important changes in the installation.

Periodic tests are the regular routine seasonal checks to determine whether the relays are in satisfactory condition and to locate and correct any irregularities that may have developed since previous tests. These tests are usually made at least yearly.

Surveillance tests are made to locate the cause of some particular known failure or suspected failure to operate properly. If relay operation is analyzed carefully and all cases of possible or known incorrect operations are followed up by field surveillance tests, the periodic test assumes considerably less importance and may be made less frequently.

Development tests are made in conjunction with the manufacturers and are usually staged field tests of greater range than the manufacturer's laboratory permits. Such tests serve as a check on the operating performance of new types of relays and assist in developing improvements. Development tests are usually confidential between the manufacturer and the customer, and give the manufacturer an opportunity to try out his product under actual field conditions before distributing it to the industry in general.

## HOW TESTING OF HIGH SPEED RELAYS DIFFERS FROM TESTING OF OLDER AND SIMPLER RELAYS

1. In testing high speed relays there is usually no time to read indicating meters or watch the motions of the relay parts with reasonable accuracy. It is therefore essential to use an oscillograph or to permit the cyclic motion of a relay element to perform a one-way operation (such as tripping a circuit breaker) to establish whether or not the cyclic operation was completed satisfactorily.

2. The performance of distance relays is a complex function of current, voltage, and phase angle. Polarity is of very great importance. Potential amplification may be used on low voltages. The older and simpler types of relays are not subject to these restrictions to any great degree.

3. The internal connections of high speed distance relays are very complicated. Testing is desirable to locate any factory errors or injuries in shipment.

4. External connections of high speed distance relays are more complicated than on any relays heretofore used. It is absolutely essential to make adequate tests to locate and correct any errors in drawings, or on the part of the construction crew.

5. In most types of distance relays a sharp cut-off, or distinction between operating and non-operating conditions, is essential. Consistency in operating limits is also very important. The operating characteristic of older relays is a simple continuous function of amperes or kilowatts instead of being a discontinuous or stepped characteristic.

6. The operating element of the older standard relays is simple, and slow moving, and one man can easily observe its performance on tests. On reactance type distance relays, it may be desirable to observe the starting unit, ohm unit, time unit, and two auxiliary relays during test.

7. The general principles of the older type of relays have not been changed for years and nearly all power company test men are familiar with them. The distance relay is new and different and rather complicated, and considerable experience and educational effort is necessary in establishing an adequate testing personnel.

8. The factory instructions on low voltage tests of distance relays are rather inflexible and incomplete. There are no factory instructions on staged testing. Practically no information is available for companies desiring to utilize staged tests, because only relatively few power companies make staged tests and they have not published any comprehensive description of the operating procedure they have developed.

9. In testing high speed distance relays, it is necessary to check the application data, as well as the relay performance. That is, it is desirable to check the line constants such as reactance and impedance.

## EQUIPMENT USED IN TESTING

The equipment used in the testing of high speed distance relays includes the following: oscillograph, adjustable phase shifter, tapped reactor, phase angle meter (precision type), variable resistors, indicating voltmeters, indicating ammeters, megger, and cycle counter. Although testing can be done without an oscillograph, the use of the oscillograph will save time and money and give quantitative results of consistent accuracy that cannot be obtained by any other method.

No special tools are required for distance relay work, other than the usual tools carried by meter and relay repair men. Small socket wrenches and screw drivers of the type used by telephone repair men for telephone relay maintenance are especially con-

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venient. In some cases the distance relay manufacturers can furnish one or more special wrenches used by their assembly men and these will be very convenient, especially on development tests.

The special facilities required for staged field tests are described in detail later.

### LOW VOLTAGE VERSUS STAGED TESTS

Low voltage tests are adequate for the following purposes: locating loose connections, locating broken leads, checking polarity, measuring resistance, testing insulation resistance, checking reactance indication, investigating performance of contacts as to sticking or sparking, checking timing, and otherwise determining the mechanical and electrical condition of the individual elements of the relays themselves. There are serious objections to depending on the results of low voltage tests alone as a check on the satisfactory operating performance of a protective installation. Staged tests will do almost everything that can be done by low voltage tests, and in some cases the low voltage tests may be unnecessary, provided the staged testing is carefully planned. In any case, much less low voltage testing needs to be done if adequate staged tests are made.

Complete low voltage tests require more equipment than staged tests. On distance relays a large amount of time is required to phase out the connections of the low voltage test equipment. In fact this may require more time than a staged test. In many cases the range of variation of electrical quantities on low voltage tests is rather limited compared to the various possibilities with staged tests. Low voltage tests give no check on selectivity, current transformer performance, potential transformer performance, and may not give any check on bell alarm schemes or on interlocks. Staged tests will give a check on the accuracy of calculations, phase markings, line constants and other system data used in short circuit calculations, speed of circuit breaker opening, adequacy of potential supply, breakdown in ratio of bushing current transformers, performance on 2-phase to ground short circuits and other conditions difficult or impossible to calculate.

### PLANNING PROCEDURE FOR STAGED TESTING

Much of the description given below is common to all staged tests of high speed distance relays on transmission systems, but is given in view of the lack of published information on the actual procedure. The value of the results obtained from staged testing is very largely dependent upon the time and skill available for working out the test procedure. Staged tests on any system become more important and valuable from year to year, because the experience obtained in previous tests can be utilized as a basis for planning future tests.

The risk to equipment is negligible. Staged tests of all kinds have been carried on on this system for 8 years. Interruptions to service on account of staged tests have been negligible.

Very little information is available from manufacturers on staged testing. On account of the need of time to make plans for staged tests, it is desirable to plan these tests at least one week ahead of time if possible. In emergency, staged surveillance tests of limited scope have occasionally been run on less than 12 hours' notice, but conditions are not always such as to permit this procedure. The certainty, accuracy, and utility of the results will be more or less directly proportional to the time spent in planning. Procedure in arranging for staged tests will usually follow more or less the following outline:

1. Determine scope of tests.

Determine the general scope and extent of the tests. This really amounts to listing the questions to be answered by the tests and determining the emergency operating conditions which should provide the answers to these questions.

2. Arrange for service interruptions.

Make arrangements with the commercial departments or others concerned for permission to interrupt customers by appointment, or if there will not be any interruptions, investigate the effect of surges or voltage variations and get the consent of those concerned. If tests are to be made on the high voltage system, it is well to notify interconnecting companies.

3. Coöperate with communication organizations.

Unless all the tests are to be phase-to-phase short circuits, and there is no possibility of accidental or intentional faults to ground, all communication companies likely to be affected by ground current should be notified. While this can sometimes be done on short notice, it involves considerable expense and loss of time to stop field crews and have them wait until the tests are over, and it is much better to have other work planned for them a few days ahead of time.

In a few cases involving main toll routes it may be impossible to re-route all traffic except late at night or on Sunday. Occasionally where induction is expected the telephone company will have the operators turn down the lines against traffic. This considerably complicates the test schedule and generally results in making it very difficult to get through long distance calls for dispatching or to communicate with the telephone test board. It is therefore desirable to insist that the telephone company either re-route affected lines, or notify the power company dispatcher before turning them down to traffic.

The communication companies will frequently desire to make tests of their own at the same time the power company is testing and are usually willing to interchange data and observations. This is of considerable assistance to the power company, especially in case of the telephone company, since the Bell System generally makes available considerable oscillographic equipment and trained observers, and it may provide facilities for measurements that the power company cannot easily handle.

As will be noted from the above suggestions it is vital that the operating department of the power company work in close coöperation with the plant departments of all affected communication companies in planning and executing the tests.

Needless to say, the same notification should be given the telephone department of the power company.

4. Consider power system load conditions.

In many cases the schedule for the tests will be governed by load conditions on the power system. Certain tests may not be economically practicable except under certain generating and load conditions, and the tests should be planned far enough ahead to permit them to be carried out successfully with the minimum additional expense for power.

5. Testing advantageous at time construction is completed.

As nearly as possible the starting of staged tests should be synchronized with the completion of construction. Testing before construction is completed is likely to be a waste of time, since there is no assurance that control wiring may not be changed. If construction is completed before testing is begun, major equipment should not be cut in service until protective equipment is completed and finally tested. The arrangements that held during construction should be maintained until testing is completed. Cutting in power equipment or lines initially without protection or with untested protection results sooner or later in serious trouble for the relay department, including lack of confidence in personnel and equipment. With these factors in mind it is usual to plan installation testing to begin immediately after construction is completed, allowing some time for unexpected delays in completing construction. If the construction crew is released before testing is done, it is generally advisable to keep at least a switchboard wireman so as to change control wiring as required to get correct phasing. Some companies do not put up meter and relay connections permanently until after final tests, but this has the disadvantage that it is difficult to complete these connections in a permanent manner during the tests, and if the work is done later it cannot be checked. Every effort should be made to have all control changes completed before or during testing, so that there is a minimum possibility of unsupervised and untested changes afterward.

## 6. Predict fault currents.

The approximate magnitude or limits of expected fault currents should be determined by calculation or on a short-circuit table, and furnished to the test men. These data will determine the ranges of oscillograph shunts, the ratios of current transformers, potential transformers, and indicating meters.

## 7. Secure good ground connection.

The faults should be placed at a location where there is a good ground connection, if ground faults are to be made, or if there is any possibility of accidental faults to ground. Where this precaution is not available it is necessary for all observers to keep possibly 100 ft away from the fault, and avoid any connection of instruments in the circuit between the fault and ground. Where good ground connections are provided, the ordinary insulation in instruments and control leads is sufficient against the rise of ground potential, and there is no danger to observers unless the ground lead is touched. It is good practice to make ground resistance tests with a ground megger and to see that all grounds at the point of test are solidly tied together and are of sufficient conductivity that they will not burn open.

## 8. Maintain company communication facilities.

Arrangements should be made to preëmpt the communication facilities needed for dispatching during the tests, and other departments should be given sufficient notice, so as to incur the minimum inconvenience to routine traffic on the company telephone lines. If this is not done considerable expense and unsatisfactory test results are likely to result from delays in switching caused by lack of communication. Without constant communication any incorrect relay operations or unexpected difficulties may interrupt service to customers, and it is therefore desirable that points involved in switching and testing should have 1 and preferably 2 means of communication at all times during the tests. It is generally desirable to maintain telephone communication between all points affected, for several minutes before and after each test. This also facilitates getting a prompt record of the test results and restoring service quickly. However, on ground tests the company telephones may have to be disconnected by opening the entrance switch, if induction is unusually heavy and if communication during the fault is not absolutely required. It is also desirable to have a telephone man pull the carbon blocks on the telephone protectors if the rise of ground potential is above that required to ground the carbon blocks but below the flashover point of the rest of the inside wiring. In synchronizing test procedure between distant points without communication, telechron clocks with second hands are of great service.

## 9. Arrange for personnel necessary.

The personnel present at the scene of the test or at strategic points on the system will naturally vary with the nature and extent of the tests, but in general there should be men present to read the test instruments, operate the oscillograph, develop films, handle dispatching, make calculations (in case of unexpected set-ups), check relay performance, make permanent changes in wiring, and keep the communication equipment working. The relay engineer or the head of the system operating department is likely to be in general charge of the tests and is generally present at a point where he can keep in close contact with the dispatchers and with the relay men. If some of the functions mentioned are handled by other departments, it is desirable to have a department head or supervisor from each other department available at the same point, so that decisions can be promptly made and carried out.

The relay engineer should have available general system short-circuit data, wiring diagrams, instruction books, relay settings, and all the necessary information to check the results of the tests as they are obtained, and to modify the schedule of tests as required in order to obtain the most valuable data.

## 10. Various types of artificial faults.

On most relay tests it is desirable to observe the performance of the relays under all fault conditions: single phase to phase, 3-phase to phase, single phase to ground, and 2-phase to ground. On distance relays one of the surest tests of correct phasing and connections is for the relays to clear a distant fault in the same time for both single and 3-phase conditions. (This assumes delta connections of current transformers.) On distance relays it is also desirable to make tests with power supply from either end and from both ends. This last condition is difficult to meet, unless the line has a tap with a switch in it. So far as we know, there has never been developed any satisfactory means of placing a temporary fault on a hot transmission line with power supplied from both ends, except to close a branch line switch. If fuse wire is pulled across the line with a paraffined rope there is some possibility of damaging the line, unless high speed relays and breakers work perfectly. On moderate voltages, the most successful scheme has been to fasten a copper ring several inches in diameter on the end of each phase of the bus and pull a treated rope through the rings. On one portion of the rope a fuse wire is wrapped between the strands to start the arc. The rope does not last long as it finally becomes carbonized. Furthermore, tests involving rope without other insulation cannot be made except in dry weather. Where the fault can be placed on the line by closing an air break switch or oil switch either a solid fault or arcing fault can be provided. Solid faults were at first favored as being somewhat quicker and easier to handle, but we now use arcing faults almost altogether. Arc faults can be started by fuse wire, wet rope or cord (preferably soaked in salt water), or by small copper wire. If copper wire is used, calculation should be made to be sure it will fuse quickly enough for the purpose of the test. The arc from a fuse has the advantage that it will clear as soon as power is removed. Air break switches are not seriously burned by closing on to faults but of course should not be opened unless the fault clears. At 110 kv arc faults around 20 ft can be maintained, although we normally use about 4 ft or the length of an insulator string. At 2,300 volts it is impossible to maintain an arc more than a few inches, but at 154 kv the arc can be drawn out to surprising distances. Dependence therefore should not be placed in separating the arc terminals to put the arc out as it is pretty sure to hang on until the power is cut off. If there is any breeze present the arc is likely to travel a considerable distance, unless it occurs on top of horn gaps or between other isolated high points. Sufficient overhead clearance should also be provided on arc faults as the arc will rise to surprising heights. Unless a ground fault is made, adequate clearance should be provided so that the arc cannot unexpectedly go to ground (and probably interrupt communication). Almost no interference with communication is experienced on straight phase faults. In placing solid faults, conductor of the same size as the transmission line should be used. Ground chains will not stand this service as they arc between links and are likely to burn in two on a single test. The most convenient way of placing single end faults on a transmission line is to place a solid fault across the bus side disconnecting switches of an oil circuit breaker and then close the breaker on to the line. If the disconnecting switches are 6-pole gang operated, the coupling between the line and bus side operating bars can be removed so as to close the line side disconnects.

## 11. Provide back-up relay protection.

It is well to provide back-up protection so that if some particular circuit breaker fails to operate the fault will not stay on the system indefinitely. It is general practice to block one or more breakers to insure uninterrupted service to important customers during tests, especially since the relays under test are likely to have their time set up to facilitate observation. To permit better observation of the performance of distance relays during fault conditions it is usual to open the trip circuit of the relays being observed if there is another breaker which can clear the fault. It is always desirable to use first a breaker and set of relays at some other station which has been tested previously to perform the actual function of clearing the short circuit. During these early tests the new relays may be observed to make sure that their phasing, polarity, etc., is correct, after which they may be used to clear the short while the details of their operation are being studied.

## 12. Time between successive tests.

The usual time between tests will vary from 15 to 60 min (although the writer witnessed a large series of tests on one system run on 5-min headway). It is desirable to notify the communication companies before each test. On development tests it is very difficult to follow a pre-arranged schedule.

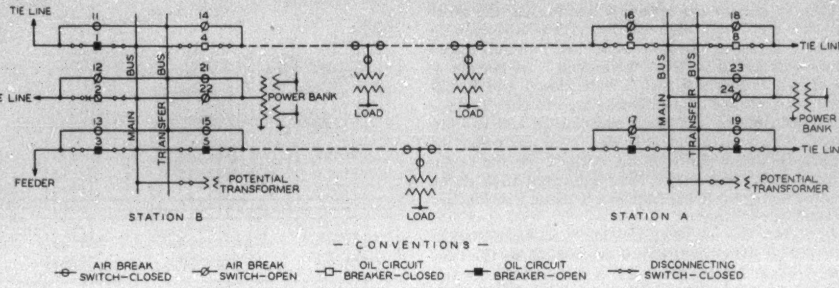

FIG. 1—ONE LINE DIAGRAM OF 2 SWITCHING STATIONS, ILLUSTRATING A TYPICAL STAGED TEST

## DETAILS OF A TYPICAL SHORT-CIRCUIT TEST

To illustrate the detailed test procedure in a typical case reference should be made to Fig. 1, which is a one line diagram of 2 switching stations on the Tennessee Electric Power Company's system. Station *B* had been thoroughly tested several months previous while station *A* had just been completed with the switching arrangement shown. Station *B* secured a clearance on circuit breaker 2 and placed a 3-phase short circuit on the line of this oil circuit breaker. The tie line on circuit breaker 8 (station *A*) is a direct tie to a generating plant where it is tied into the system. There are no loads tapped off of this tie line. On the other hand the tie line on circuit breaker 9 has a number of tapped loads some of which are very sensitive to voltage changes. The tie line on breaker 2 has tapped loads but these were supplied from the other end of the tie line by opening a sectionalizing air break switch at the load nearest station *B*. The particular switching arrangement shown is for the testing of the relays on breaker 6. It can be noted that the only customers subject to any severe disturbances are those tapped off of the tie line between breakers 6 and 4. Of course the system was subject to a slight voltage drop in feeding the short circuit by way of tie line 8.

For this particular test the relays on breaker 2 were allowed to operate with their normal settings. After the oscillograph had been started, breaker 2 was closed onto the short circuit and allowed to open by relay. At station *A* the instantaneous elements of the distance relays on breaker 6 were set for a reactance of 110 per cent of the line reactance from station *A* to station *B*. This follows the principle of leeway in that the relays are allowed 20 per cent in their final settings. Their trip circuits were disconnected from the breaker trip coil and instead a resistor arrangement was used so that the relay targets would operate and the time when the relays would have tripped the breaker would be recorded by the oscillograph. The operation of the various elements of the distance relays on breaker 6 was observed during the test while the oscillograph film gave considerable data on the transmission line constants and also recorded the speed of the relays for instantaneous operation.

Since the relays operated successfully on this test the relays on breaker 2 were set so as to give a total time of approximately one sec. The relays on breaker 6 were then set so that their instantaneous elements would operate on a reactance of 90 per cent of the reactance of the line from station *A* to station *B* and their intermediate time elements were set to operate for a reactance 110 per cent of this value. These values allow the same margin over the final settings as before. The intermediate time was set at 60 cycles and the relays arranged to operate the oscillograph only as in the previous test. These special connections of the relays were made by means of test jacks inserted in test blocks permanently installed on the switchboard, so that no part of the permanent switchboard wiring was changed. In this manner the possibility of leaving a set of relays reversed or inoperative after the tests are finished is reduced to an absolute minimum. Breaker 2 was closed onto the short and allowed to relay as before. During the short circuit, observers read the position assumed by the reactance arms of the distance relays.

Following these tests a similar test was made except that 2 phases of the line were shorted together instead of all 3. The relay corresponding to the shorted phases should indicate the same reactance as it did during the 3-phase short-circuit test (assuming delta connected current transformers). The final check on the distance relays of breaker 6 was made later when an arcing fault was placed at station *A* on the line side of breaker 6. In this case the relays were allowed to trip the breaker. By means of the oscillograph a check was obtained on the accuracy and speed of the relays for nearby short circuits and in addition the performance of the oil circuit breaker could be analyzed.

In testing the relays on oil circuit breaker 8 a short circuit was placed at the far end of the tie line. During the earlier tests the performance of the relays on this circuit breaker had been observed with regard to phasing and polarity by reversing these relays and blocking their trip circuits with test jacks. It was therefore thought unnecessary to arrange for the breaker at the far end of the tie line to clear the short circuit. For these tests station *B* was arranged so that all oil circuit breakers were closed and all transfer bus air break switches were open. At station *A* oil circuit breakers 6 and 7 were closed and 9 was open. Oil circuit breaker 8 was used to close in onto the short circuit. Air break switches 23 and 19 were closed. This arrangement was used in order to supply sufficient short-circuit current for the tests. A good many customers were subjected to a slight drop in voltage but the impedance of tie line 8 acted as a cushion for them.

In testing the relays on breaker 9, it was desirable to cause as little disturbance as possible to the customers located along this line. Consequently for the early tests, air break switches 18, 24, and 19 were closed, and oil circuit breakers 6 and 7 were closed while breaker 8 was open. Breaker 9 was used to close in on the short circuit at the end of tie line 8 by way of the transfer bus at station *A*. Of course an air break switch at the nearest customer on tie line 9 had been opened before the test. After the relays on breaker 9 had been checked in this manner as thoroughly as necessary, the system set-up was changed and an arcing short was placed at the far end of tie line 9. Breaker 9 was allowed to open by relay and to reclose instantly by means of its regular instantaneous reclosing relay. In this manner considerable data on the line constants was obtained by means of the oscillograph, with only one disturbance to the critical customers on tie line 9.

Many expedients may be used where the full switching facilities shown on Fig. 1 are not available. For example, certain makes of 6-pole gang operated disconnecting switches may be made to operate 3 poles at a time by removing one pin in the operating mechanism. At times it is necessary to place a short circuit on the bus side of the oil circuit breaker and reverse the relay connections by means of test jacks.

## Typical Low Voltage Tests

In making installation tests of distance relays it is customary to give them a thorough mechanical inspection as soon as the switchboard portion of the construction is completed. Most manufacturers give rather thorough and specific instructions regarding the mechanical adjustments and clearances of the various portions of their relays. One possible point of disagreement is that the manufacturers have been insisting on a rather large amount of wipe in their various contacts. Operating companies have found this practice undesirable in many cases and the modern tendency is to use better contacts and to require less wipe. Some makes of relays are easier to adjust mechanically on account of the fact that larger forces are present in the relays during operation. Relays using an outside source of power such as the d-c control circuit for the operation of timing units, etc., will of course have more volt-ampere burden available for operating their distance measuring elements. Some mechanical adjustments are best determined by low voltage electrical tests.

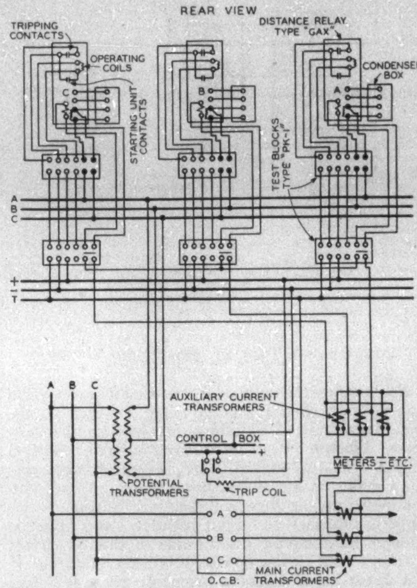

Fig. 2—Correct Phasing for a Particular Type of Distance Relay When the System Phase Sequence Is *A, B, C*. Note the Use of Test Blocks

Adequate testing of relays presupposes adequate test facilities, such as the test block arrangement shown in Fig. 2. The particular relays are General Electric type *GAX* and the subsequent discussion refers principally to this type of relay. It is well to adopt a standard test scheme in the early stages of applying a given type of relay to a system and to refrain later from making even minor changes in this test scheme unnecessarily.

Low voltage testing can be of great assistance before the staged tests in checking the external connections of the distance relays. In Fig. 2 is shown the correct phasing for distance relays when the system phase sequence is *A, B, C*. When the circuit shown in Fig. 2 feeds a unity power factor load the current and potential of each distance relay should be in phase and should be in the same relative direction in the relay (vertically) at any instant. To check this, a phase angle meter, ammeter, and voltmeter may be connected in the test circuit as shown in Fig. 3.

A scheme of connections for the low voltage testing of the relays themselves is shown in Fig. 4. A somewhat simpler arrangement may be made by the use of a tapped reactor which takes the place of the phase shifter and phase angle meter but the arrangement is not nearly so flexible particularly when testing the starting units of the relays.

In testing distance relays by means of low voltage

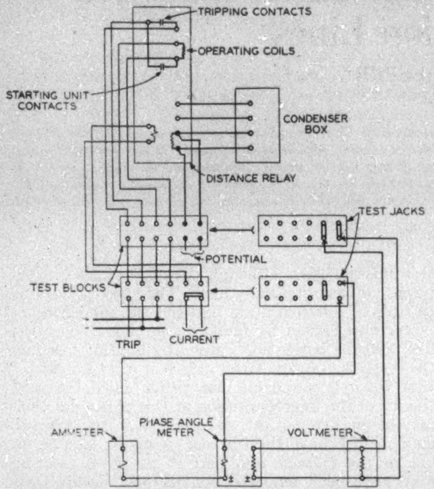
TRIPPING CONTACTS
OPERATING COILS
STARTING UNIT CONTACTS
CONDENSER BOX
DISTANCE RELAY
TEST JACKS
POTENTIAL
TEST BLOCKS
TRIP
CURRENT
AMMETER
PHASE ANGLE METER
VOLTMETER

Fig. 3—Connections for Checking Current and Voltage Phase Relations of the Relays Shown in Fig. 2

test equipment it has been found advantageous to check each portion of the relays separately and to conclude the test with an overall check of all of the elements operating together.

Considerable leeway can be allowed in the pick-up of the starting unit since this unit does not perform the distance measurement. The principal quantities to be determined are an approximate curve of amperes to pick-up against applied volts for the phase angle of maximum torque, and two or more curves of current against phase angle with the applied voltage held constant. It is evident that at the lower voltages the time of operation of the starting unit assumes importance instead of its pick-up value. Accordingly connections are made so as to check the time of operation of the starting unit contacts for low voltages and extremely low currents for both resistive and reactive faults. The operating times thus secured are much higher than the actual time of operation encountered in service. This latter time should be obtained by means of an oscillograph during staged tests and the higher values used to check internal connections, relay adjustments, etc., and to check the operation of the potential amplifying equipment of the relay.

It has been found good practice to calibrate the reactance unit with considerable accuracy at the nearest even scale division to the final setting of the instantaneous knob. This can be done quite readily by adjusting the pole pieces of the distance element while the desired current, voltage and phase angle are being held constant on the relay. After the distance unit has been set in this manner it is of considerable value to check this unit at different portions of the scale and also on different ohmic taps since an emergency change in setting might become necessary sometime in the future. Besides this test the ohm unit is checked by taking a curve of the indicated reactance against secondary current with constant reactance. The time unit of the relays may be checked at various points on the scale against the cycle counter of the test equipment.

In making the final overall check of a distance relay it is well to employ the principle of "leeway" or "safe margin." If the operating time is higher than expected it is a fairly simple matter to determine which portion of the relay is responsible for the additional time. Any extra time introduced by the ohm unit may usually be eliminated by making sure that the instantaneous contact does not have any appreciable wipe. By holding the contacts of the starting unit and ohm unit closed it is possible to read directly the time delay introduced by the auxiliary relays and to adjust these relays whenever necessary.

### Acknowledgment

The writer wishes to acknowledge the able assistance of W. R. Brownlee, relay engineer of The Tennessee Electric Power Company, in preparing the manuscript of this paper. Much of the test procedure aside from the inter-company arrangements was developed by Mr. Brownlee.

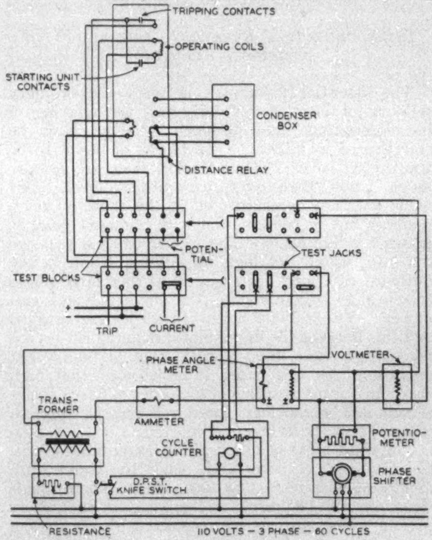
TRIPPING CONTACTS
OPERATING COILS
STARTING UNIT CONTACTS
CONDENSER BOX
DISTANCE RELAY
POTENTIAL
TEST JACKS
TEST BLOCKS
TRIP
CURRENT
PHASE ANGLE METER
VOLTMETER
TRANSFORMER
AMMETER
CYCLE COUNTER
POTENTIOMETER
PHASE SHIFTER
D.P.S.T. KNIFE SWITCH
RESISTANCE
110 VOLTS – 3 PHASE – 60 CYCLES

Fig. 4—Connections for Low Voltage Testing of Relays

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## Discussion

For discussion of this paper see page 824.

# Relaying of High Voltage Interconnection Transmission Lines

BY H. P. SLEEPER*

Member A.I.E.E.

***Synopsis.***—*This paper presents an operating engineer's point of view of the practical and theoretical problems presented in applying relays for the protection of high voltage open wire interconnection transmission lines. It points out that the relaying of such lines involves problems which are not ordinarily present in the relaying of intra-system lines. These problems are enumerated and the extent to which modern relaying meets them is discussed. It is shown that the most satisfactory schemes are very expensive and the cheaper schemes are not entirely effective. The limitations of available schemes are discussed and their economics compared. A theoretical solution is proposed.*

THE INTERCONNECTION of large power systems by means of high voltage transmission lines has expanded so rapidly in the past ten years that it no longer involves any major engineering problems in the usual application. This excepts the problem of stability which may or may not be present. The protective relaying of such lines has, however, not become standardized and the number of different schemes in use today indicates that complete agreement has not been reached. Moreover, the economics of the various schemes vary over wide limits. Both phases of the subject are worthy of the engineer's study, and it is the purpose of this paper to discuss the merits of the principal schemes and indicate their comparative economics.

## INTERCONNECTION RELAYING COMPARED WITH ORDINARY RELAYING

The essential differences between the ordinary relaying of intra-system lines and the relaying of interconnection lines between systems may be enumerated as follows. The blocks of power to be transmitted over interconnection lines are usually much larger than over intra-system lines. This alone does not necessarily effect the choice of relay schemes but in combination with the next point it presents a limitation. The second point is that the lines are usually of high impedance, being in the ordinary case long open wire lines with large phase spacings to accommodate the high voltages employed. The stability limits of such lines are critical and this imposes the first definite requirement on the relaying of these lines, namely, that of high speed operation. In this paper it is assumed that high speed circuit interruption of the order of 6 to 8 cycles is supplied where high speed relaying of approximately 2 cycles or less is employed.

The third point of difference is the peculiar conditions imposed on such relays while the systems are oscillating with respect to each other. These conditions may also be present on intra-system lines where various power sources are connected by the system transmission lines, although the magnitudes of such power swings are usually less. The relays should be capable of differentiating between the conditions of power flow caused by faults on the interconnection line, and the power flow caused by hunting between the systems. In the latter case it is most important that the relays remain inoperative since the continuity of the interconnection at this particular time may be most important, as the cause of the swinging may readily have been a case of major trouble on one of the systems and part of its power sources may have been rendered unavailable. Hence it is vital that the interconnection transmission line remain in service to deliver emergency power to the system whose load may now exceed the connected generation. On the other hand the relays on such a line should be capable of detecting power swings which indicate severe out-of-step conditions. When such conditions occur it is usually best for the systems to be separated and the relays should accomplish this.

## REQUIREMENTS OF THE IDEAL RELAY SCHEME

Hence we may enumerate the requirements of the ideal relay scheme for the protection of an open wire high voltage interconnection transmission line, as they are considered in this article, as follows:

1. The relay scheme shall be inherently selective.
2. The relays shall operate instantaneously (2 cycles or less) when a fault occurs.
3. The relays shall operate simultaneously on the ends of the line.
4. The relays shall be unaffected by swinging conditions between the systems as long as the systems do not become out-of-step, in which case the relays should operate.
5. The relay system should provide protection for both phase and ground faults.

There are a few schemes of relay protection which meet most of these requirements as far as phase to phase faults are concerned and these will be discussed first. The detection of ground faults presents more complications in general. The distance type of phase relay protection will be considered first, not because it is the best scheme available but because it is the one which is probably in most common use on interconnection lines constructed in the last few years.

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33-73

### DISTANCE RELAYING

Distance relaying has many inherent advantages to recommend it, such as its feature of automatic selective operation by fault location, its simplicity, and its low cost. It operates instantaneously for a large proportion of faults on the line. It also provides back up protection, usually in the form of self-contained time element devices which are set into operation by other distance measuring units within the relay. But it cannot be said that distance relay protection meets the high speed requirement since its principle of operation leaves a zone of approximately 15 per cent of the line at the far end for a safety factor in distance differentiation. Faults in this zone are detected by the operation of time delay devices. Therefore it may be said that the distance relay meets the speed requirements only 85 per cent, and the distance relay protection of both ends of a line meets the requirement only 70 per cent, since faults in the two 15 per cent zones are not disconnected instantaneously or simultaneously. For the purpose of discussion it is assumed that the number of faults on a line will be evenly distributed over its length. Hence the measure of the high speed ability of a relay scheme is that percentage of the length of the line on which faults are cleared instantaneously. The writer chooses to set distance relays conservatively with the balance point at 85 per cent of the length of the line. This allows as high as a 10 per cent shifting of the balance point to occur from all causes such as changes in generator schedules, outages of intra-system lines, and equipment and personnel errors, without endangering selectivity.

The time of operation of the distance relay scheme varies from a minimum of 1 cycle in 70 per cent of all fault locations, to a first time zone operation for the remaining 30 per cent of fault locations, the time for the 30 per cent zone being usually a minimum of 20 cycles and frequently higher as conditions dictate. A time of 20 cycles permits a safety factor of 100 per cent when selecting with a 2-cycle relay and an 8-cycle circuit breaker. If fault locations multiplied by operating times could be averaged it might be said that the average operating time of the distance relay scheme is $\frac{(70 \times 1) + (30 \times 20)}{100} = 6.7$ cycles. It might therefore be said that the average operating time of distance relay protection approaches that of a high speed scheme.

Although the distance relay does not usually afford true high speed protection, there is one condition where this limitation is avoided. This is the case, sometimes found in practice, where a high voltage line has transformers at each end and the line circuit breakers are connected in the low voltage sides of the transformers. This makes the transformers a part of the line and their lumped impedances permit the distance relays to be set so that all faults on the line, and in parts of the high voltage windings of the transformers, will cause operation of the instantaneous elements of the relays. This causes all line faults to be cleared instantaneously and simultaneously at both ends.

The instantaneous operation of distance relays over the initial 85 per cent of the line requires that the directional elements of these relays shall be of a high speed nature. This is not difficult of attainment if the fault is not too close to the bus, or if it involves only two phases. But a three-phase fault close to the bus may give a voltage of only 1 or 2 per cent of normal, being mainly the resistance drop in the arc. There is no voltage controlled directional element available which will operate instantaneously under these conditions. It is therefore important, where possible, to take relay potential for the directional elements only from the opposite side of the station power transformers. Thus any feed back through these transformers gives an impedance drop which will increase the voltage on the relay directional elements and speed up their operation.

The economics of this type of protection are very favorable since no special high voltage or low voltage equipment is required and the cost of such an installation compares with that of an installation of standard directional overcurrent relays. An accurate replica of voltage conditions on the high voltage circuit should be supplied to the relays but high voltage potential transformers are not absolutely necessary, as bushing potential devices used for this purpose are in successful operation. (See "Bushings Supply Potential," by H. A. P. Langstaff and P. L. Langguth, *Elec. World*, Nov. 24, 1928, p. 1043–5. Also "Relays Operated From Bushing Potential Devices," by P. O. Langguth and V. B. Jones, *Elec. World*, June 25, 1932, p. 1092–6.)

Distance relays are made today in both the impedance and reactance types and their comparative merits have caused considerable controversy. Theoretically the use of the reactance principle with distance relays on open wire lines offers advantages because of the elimination of any consideration or effect of arc resistance. On the other hand the fact that the reactance relay will operate on normal system load characteristics, namely, small apparent reactance and high apparent resistance, complicates the use of this principle. The introduction of a fault detector relay is the solution of one manufacturer. Another places a minimum reactance pick up on the reactance element such that normal load reactances will not be in the zone of operation. Both of these schemes have disadvantages; the former delays the operation of the relay while the fault detector element operates; and the other causes the relay, by the recommendation of the manufacturer, to be restricted to short line applications.

Each of the two types of distance relays has its peculiar advantages. The impedance principle is the simpler since only a consideration of ratios of quantities is concerned because the torque of such a relay is proportional to $I^2 - E^2$. The torque of a reactance relay involves the angle between the current and voltage, being proportional to $I^2 - EI \sin \phi$. This has the distinct advantage that the resistance of the entire fault circuit is eliminated from all calculations. But it complicates the operation of the relay since the angle $\phi$ may vary during the development of a fault, or after the clearing of a fault when hunting may exist between the interconnected systems. The same may occur for faults on the taps of tapped transmission lines. Such lines offer problems to any type of distance relay since the voltage at either terminal is not a true measurement of the distance to the fault by reason of the increased voltage drop due to the presence in the tap circuit of the summation currents from the two sources.

In the writer's opinion the use of the reactance principle, except on short lines where arc resistance may represent a large factor in fault impedance, does not seem to be as desirable as the simpler impedance principle. Furthermore from a practical standpoint, reactance relays are more difficult to calibrate in service than impedance relays.

Experience with distance relaying shows that undesirable operations sometimes occur due to changes in the quantities presented to the relays. These changes are caused by developments at the fault as time progresses. The original relay interpretations are therefore more apt to give correct distance readings. This suggests the desirability of so modifying the design of distance relays that the original measurements determine the time of operation. This would prevent arc resistance, for instance, from increasing to the point of falsifying the distance measurement of an impedance relay and would thus eliminate the main objection to this relay as applied to the short circuit protection of short lines. On longer lines of the type under discussion such errors are negligible.

The operation of distance relays under conditions of system surging leaves considerable to be desired. The impedance type relay in general seems to offer the better chance of holding the systems together under such conditions since only ratios of currents and voltages are being compared in the relays. But it may give delayed operation for an out-of-step condition for the same reason. The reactance relay will be more sensitive to hunting and should operate readily for out-of-step conditions. It is, however, more apt to trip incorrectly during surging because at one point in the rotation of currents and voltages the relay is measuring system resistance only. The ability to separate interconnected systems during instability at the most desirable geographical point may offer a difficult problem with any type of relaying. Some special form of out-of-step relay is usually the simplest practical answer.

There are two schemes which compare directly with the distance relay for the protection of interconnection lines, both of which suffer in comparison of economics but have distinct engineering advantages and some practical disadvantages. The first is pilot wire relaying.

### PILOT WIRE RELAYING

Pilot wire relaying is an old art still somewhat in use but comprising only a small percentage of total system relaying today in this country. Its particular advantages as applied to the protection of interconnection lines are its inherent selectivity and its feature of simultaneous operation at both ends for all locations of faults. The pilot wire relay scheme may be made to meet these two requirements perfectly and is the only scheme in common use today of which this is true.

Pilot wire relaying is inherently a high speed scheme and operates in an overall time of 1 to 2 cycles in its most preferred forms.

Another advantage of pilot wire relaying is its ability to operate independently of system conditions such as connected generating capacity and outages of transmission lines. The practical advantage of this phase of any relaying scheme is paramount to the operating engineer. The necessity for special calculations and the resetting of relays for different system set-ups is the bane of the operating man.

A further advantage of pilot wire relaying is its ability to protect for both phase and ground faults, using the same set of relays. This feature is perhaps one of its most desirable characteristics since the range of current values for these two types of faults may run as high as nine to one even on a solidly grounded system. These data are a matter of actual record on a large 220-kv interconnection system and were taken from automatic oscillograph records. Some schemes of pilot wire protection, however, use separate phase and ground relays.

The obvious disadvantages of this type of protection are the high initial capital cost, the maintenance cost and the operating hazard of maintaining pilot wires between the terminals of the high voltage line. A further disadvantage of this type of protection is that it usually does not provide inherent back up protection for faults beyond its own terminals and such protection must be supplied in the form of additional relays. All of these features tend to make an installation of pilot wire relays expensive as compared with distance relays, or in general with any other types of protection involving only terminal equipment, with the possible exception of the carrier current scheme.

Some of the more recent schemes of pilot wire protection have innovations which from an engineering standpoint render them inherently superior in their general protective features and economics as compared with the older types of this scheme of protection. Some of these schemes were described in "Relay Systems Utilizing Communication Facilities," by J. H. Neher, published in ELECTRICAL ENGINEERING for March 1933, p. 162–8. Such schemes are in effect merely means for comparing relay interpretations at the two ends of a line by utilizing the pilot wires for d-c circuits only and for simultaneously tripping the two terminal circuit breakers. In another arrangement, sometimes called "transferred tripping," the pilot wires are used to permit a standard relay scheme at either end of the line to trip the other end as well, thus completely disconnecting the line with a relay time equal to that of the faster relay system at either end. In general such schemes are distinctly superior to the a-c pilot wire schemes which usually necessitate low resistance pilot circuits and some of which have large normal electrical losses and require special current transformers.

These points are of particular significance if leased pilot circuits are to be employed since the use of the direct current prevents interference with adjacent communication circuits in the same cable. Only very small values of low frequency alternating current can be transmitted over circuits leased from the communication companies, and thus a-c pilot wire schemes usually require the installation of special pilot wire circuits.

Another point of practical importance in connection with the use of a-c and d-c pilot wire schemes is that of providing means of insulating the terminal relay equipment from the pilot wires. The latter may operate at, or be raised by ground fault currents to, a higher value of potential above ground than the terminal equipment and protection must be provided. In the case of the a-c scheme it can usually be accomplished rather simply by using insulating transformers. But since this is impossible with the d-c scheme it is usually accomplished by the introduction of insulation between the terminal and line parts of certain relays. It is important that such insulation be provided and a circuit established for the relief of dangerous overpotentials. The necessity for such provisions are among the disadvantages of this scheme of protection. Other disadvantages are maintenance hazards, sometimes aggravated by the maintenance personnel if leased circuits are employed; and the general difficulty of checking such schemes for service, particularly the older types.

It is obvious that the scheme of pilot wire relaying can be designed to meet all the requirements of interconnection relays as regards their performance under conditions of system surging. The scheme will inherently pass through blocks of power and remain inoperative, but if a severe out-of-step condition arises so that an electrical neutral is established between the terminals of the line, the pilot wire scheme may be designed to function as on a line fault. Some schemes of this type require the addition of back up or out-of-step relays to accomplish this.

The use of pilot wire relay protection on long open wire interconnection lines is very uncommon for obvious reasons. For short lines it may not be unduly expensive. For longer lines, even where the use of leased pilot circuits helps reduce the investment, the total cost is usually prohibitive unless the engineering features can be very highly capitalized. It is, however, very pertinent to note that this is the only scheme available today which meets all the requirements of the ideal system of interconnection relaying as defined in this article.

### CARRIER CURRENT PILOT RELAYING

While not yet in broad use the scheme of using the high voltage line as a pilot for high frequency carrier relay currents has proved satisfactory on test and in limited service, and is a type of protection which unquestionably offers an extensive field for future development. At the present time, however, the necessity of using expensive high voltage terminal equipment in the form of wave-traps, coupling capacitors, highly insulated control wiring, vacuum tube control devices and special generators for the tube circuits, all tend to make the scheme undesirable for general use. However, this scheme has nearly all of the inherent advantages mentioned for pilot wire relaying and on lines of considerable length would be certain to prove more economical. It eliminates some of the disadvantages of pilot wire relaying, principally the necessity for the pilot wires themselves and their attendant maintenance difficulties, and in its latest form has all of the primary features of pilot wire relaying.

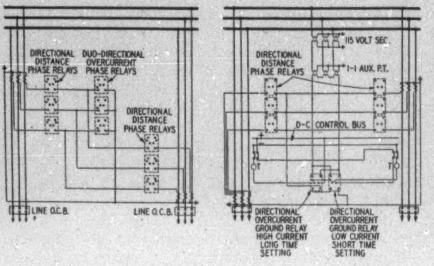
Strictly speaking, this scheme does not come in the class of high speed relaying as previously defined; that is, a scheme which energizes the trip coils of the circuit breakers on both ends of the line in a time of 2 cycles or less after the initiation of the fault. However, effectively it accomplishes almost as rapid total disconnection of the fault from the system, for all possible fault locations, as the pilot wire scheme, and averages faster than the distance relay scheme. The carrier current pilot relay scheme requires a time of 4 to 6 cycles for both circuit breaker trip coils to be energized after the start of the fault condition regardless of fault location. As previously noted, in the most preferred form of pilot wire relaying this time is of the order of 1 or 2 cycles. We have seen that the operating time of distance relay protection varies from 1 to 20 cycles depending upon the location of the fault, and may be said to average 6.7 cycles for all possible fault locations. It therefore seems fair to classify the carrier current pilot relaying scheme as high speed relaying as a matter of practical application, although actually its time of operation is high by 2 or 3 cycles. The manufacturers claim that the overall operating time of 4 cycles of this scheme can be reduced.

The engineering advantages of this scheme of relaying as used on interconnection lines are practically the same as those previously enumerated for pilot wire relaying.

The amount of special equipment at present used with this scheme is the principal disadvantage but its elimination is not an insurmountable engineering problem. The use of vacuum tubes for protective relaying may be questioned by the operating engineer, but one should not fail to recall the extensive use of tubes of this nature in devices much more complicated and operated by laymen. The use of monitoring devices with the tubes renders such an objection practically obsolete. Since the main objection to this scheme of protection is its cost it seems very probable that future developments will be in favor of the extension of this type of protective relaying.

### BALANCED RELAYING OF PARALLEL LINES

Where parallel circuits are used for interconnection lines it is common practice to apply balanced


DIRECTIONAL DISTANCE PHASE RELAYS
DUO-DIRECTIONAL OVERCURRENT PHASE RELAYS
DIRECTIONAL DISTANCE PHASE RELAYS
LINE O.C.B.
LINE O.C.B.
115 VOLT SEC.
1-1 AUX. P.T.
DIRECTIONAL DISTANCE PHASE RELAYS
D-C CONTROL BUS
+
−
T
T
DIRECTIONAL OVERCURRENT GROUND RELAY HIGH CURRENT LONG TIME SETTING
DIRECTIONAL OVERCURRENT GROUND RELAY LOW CURRENT SHORT TIME SETTING

FIGS. 1 AND 2—SCHEMATIC DIAGRAMS OF PARALLEL LINE PROTECTION

Fig. 1—Duo-directional overcurrent relays for balanced protection and directional distance relays for back up and single line protection. Trip circuits of duo-directional overcurrent relays interrupted when either line oil circuit breaker is open. Potential and trip connections omitted

Fig. 2—Directional overcurrent relays for balanced ground protection and directional distance relays for short circuit protection. Trip circuits of balanced ground relays interrupted when either line oil circuit breaker is open. Potential and trip circuits of distance relays omitted

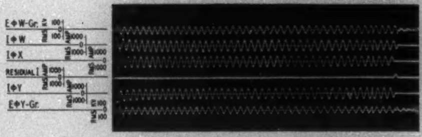


FIG. 3—AUTOMATIC OSCILLOGRAPH RECORD OF A THREE-PHASE FAULT ON A 220-KV OPEN WIRE LINE OF THE TYPE SHOWN IN FIG. 4

relaying in some form because of its engineering advantages, its general simplicity, and its low cost; also the fact that it can be applied to ground protection as well as to phase protection. However, one should not overlook the fact that single line relaying must be provided also if high speed relaying is desired under all conditions of operation, that is, with either one or two lines in service. Hence the complete solution may be the initial choice of one of the above described schemes rather than the choice of the balanced scheme for the one operating condition only, the distance relay being preferred for cost reasons if stability conditions permit.

There is, however, one very important engineering advantage to be noted in the use of balanced relaying as compared with distance relaying of parallel interconnection lines. This is the instantaneous sequential operation of the relays on the two ends of a line protected by balanced relays, as compared with the instantaneous and first time zone operation of distance relays for all faults occurring in the end zones of such a paired line. The so-called end zone is the 15 per cent of the line beyond the balance point of the instantaneous element of the distance relay. As previously described, when distance relays are used such faults lie within the instantaneous zone of the distance relays on the near end of the line, but require the first time element to operate to clear the far end. Hence the maximum total clearing time on the entire system is that of the time setting of the first time element of one relay, plus an instantaneous relay operation on the other relay plus the operating times of two circuit breakers. The minimum time would be that of the first time zone setting plus its circuit breaker and assumes simultaneous operation of the relays at both ends. But with the balanced relay system the total time involved for this location of faults is that of one instantaneous relay plus one circuit breaker on one end, plus one instantaneous relay and its circuit breaker on the other end. This is of course due to the fact that after the first end has cleared, all of the short circuit current is available to unbalance the instantaneous balanced relays at the second end. Hence for all possible locations of faults on one of a pair of parallel lines it may be shown that with either balanced or distance relays approximately 70 per cent of all faults will be cleared by the instantaneous simultaneous operation of the relays on both ends; but with distance relays the remaining 30 per cent of faults will always require the operation of one time element relay and may require the sequential operation of one instantaneous relay plus one time element relay; whereas the balanced relay scheme will clear the remaining 30 per cent of faults in two sequential instantaneous relay operations. To all of these relay time values, of course, must be added the clearing times of the circuit breakers. In Table I is shown the comparative operating times of the various schemes.

It is, therefore, obvious that the balanced system of relaying has distinct advantages where it can be applied, as compared with distance relaying. It does, however, have certain practical disadvantages such as the cross connections between current transformers in some cases; the necessity for interlocking the relays with the circuit breakers at the ends of the lines to prevent the tripping of the good line while the faulted line is clearing the second end; and the hazard of tripping a loaded line while switching in the other line of the pair. All of these complications favor the use of the simpler scheme of the distance relays. A scheme to combine the advantages of both and to eliminate some of the disadvantages of each of these schemes is the use of balanced relays for two-line operation and distance relays for single line operation. (See Fig. 1.) A still simpler scheme is the use of distance relays for short circuit protection and balanced relays for ground protection. (See Fig. 2.) The latter is used on several 220-kv interconnection lines in this country and has been very satisfactory in operation.

The use of balanced relaying for short circuit protection is a very simple and effective solution to the problem of the non-operation of interconnection relays during surging between systems. However, to effect disconnection during out-of-step conditions requires the application of other relays.

## STABILITY CONSIDERATIONS

It is pertinent to consider which of these various schemes of short circuit relay protection can be expected to maintain stability of the interconnected power systems under fault conditions. This question cannot be answered in a general way because each interconnection has individual characteristics. There are interconnections now in operation which by calculation cannot maintain stability if a three-phase short circuit exists longer than 3 or 4 cycles. Obviously no protective scheme can accomplish this today when the fastest high voltage circuit breakers available operate in a minimum time of 6 to 8 cycles. But if it is assumed that the fastest relaying scheme available will be satisfactory in this respect, then the comparative abilities of the schemes may be discussed.

As shown in Table I the fastest of the schemes considered operates to clear both ends of the line in a time of 9 cycles and is accomplished by pilot wire relaying. The carrier current scheme of transferred tripping approaches the next closest with a uniform operating time of 10 cycles. The minimum operating times of two other schemes are only 9 cycles but their maximum times are considerably higher. Thus both the balanced relay scheme and the distance relay scheme would maintain stability, under the assumed conditions, for 70 per cent of all faults. But in the remaining 30 per cent of cases the clearing time of 18 cycles of the balanced relay scheme might readily cause instability; and the time of 28 cycles of the distance relay scheme would probably be prohibitive in the majority of installations under three-phase fault conditions. This legitimately raises the question whether the operating time of 12 cycles of the carrier current pilot relay scheme should be conceded as satisfactory. There will unquestionably be cases and conditions where this scheme will not operate fast enough to maintain stability but in the majority of installations it is believed that it will. This discussion also raises the question of using the values of average clearing times as a proper measure of the comparative stabilities to be effected by two protective schemes. It can be shown by calculation that an interconnection which might under certain conditions be stable when a fault was cleared in 12 cycles, would be certain to become unstable if the time were extended to 28 cycles. It follows that maximum and not average clearing times should be used for such comparisons.

Frequently an interconnection which cannot be maintained stable during three-phase short circuits will maintain stability readily during two-phase, or one-phase to ground, fault conditions. This may enable the most economical short circuit protective scheme to be applied if the limitations are acceptable. Some cases are on record where short circuit protection has been entirely omitted and only ground relaying provided. Obviously this should not be considered in lightning territory.

## Ground Relay Protection

The matter of the ground relay protection of high voltage open wire interconnection circuits is one which may present a difficult engineering problem. Furthermore, it is a most vital one since a very high percentage of all faults on such lines are single-phase to ground. In three years of operation on the Pennsylvania-New Jersey interconnection, a total of 82 faults occurred. Of these 73 or 89 per cent were single-phase to ground faults, 4 or 4.9 per cent were two-phase to ground faults and 5 or 6.1 per cent were three-phase faults. This number of three-phase faults shows clearly the necessity for short circuit relay protection on open wire lines in lightning territory. The oscillogram in Fig. 3 shows that ground relays had no opportunity whatever to function on one such fault on these lines. This fault occurred on a tower line of the type shown in Fig. 4.

When the pilot wire or the carrier current relay scheme is used, the problem of ground protection is not always present since these relays may be set to operate for both types of faults unless extremely high values of neutral impedance are used which has not been done in this country to date on lines at the operating voltages considered in this article. With any of the ordinary types of balanced relaying schemes, or any type of distance relaying, a separate relaying scheme for ground faults is mandatory even on solidly grounded systems. This problem has

TABLE I—COMPARATIVE OPERATING TIMES OF VARIOUS RELAYING SCHEMES ARRANGED IN ORDER OF MAXIMUM CLEARING TIMES

| Type of relaying | Relay time of one end | Total relay time of two ends |  |  | Total clearing time of both ends | Total time to clear fault from system (8 cyc. breaker) |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | Min. | Max. | Avg. |  | Min. | Max. | Avg. |
| Pilot wire scheme | 1 cycle | 1 | 1 | 1 | 1 cyc. + 1 bkr. opening | 9 | 9 | 9 |
| Transferred tripping carrier current scheme | 2 cycles | 2[a] | 2 | 2 | 2 cyc. + 1 bkr. opening | 10 | 10 | 10 |
| Carrier current pilot relay scheme | 4 cycles | 4 | 4 | 4 | 4 cyc. + 1 bkr. opening | 12 | 12 | 12 |
| Balanced relay scheme | 1 cycle | 1 | 10[b] | 3.7[c] | 1 cyc. + 1 bkr. opening<br>to<br>2 cyc. + 2 bkr. openings | 9 | 18 | 11.7 |
| Distance relay scheme | 1 or 20 cycles | 1 | 20 | 6.7 | 1 cyc. + 1 bkr. opening<br>to<br>20 cyc. + 1 bkr. opening | 9 | 28<br>37[d] | 14.7 |

Note: All times are given in cycles.

a. This allows one cycle for line relay plus one cycle for transferred tripping relay.

b. Equals time of relay and breaker at near end plus relay at far end.

c. $\frac{(70 \times 1) + (30 \times 10)}{100} = 3.7.$

d. Equals 1 + 8 + 20 + 8 = 37 cycles possible maximum time for sequential operation of distance relays on parallel lines.

never been satisfactorily solved by a universal scheme other than the use of pilot wire relaying or its equivalent. The use of time element directional ground relays may offer a solution but this is usually not the case with high voltage interconnections as instability may easily be caused by the delayed clearing of a ground fault, although a certain amount of time is usually permissible, the amount varying with the individual case.

A method which has been used with a very acceptable degree of satisfaction is that of a quantitative measuring scheme which uses either the first or second powers of the zero phase sequence current of the line to determine the location of ground faults. Simple overcurrent relays are used which may be set to operate instantaneously for certain locations of faults, but their zone of safe selective operation is necessarily limited because of the variations in the magnitudes of ground fault currents under various system set-ups. Hence if the scheme can be set to operate instantaneously to disconnect the line for ground faults over 75 per cent of its length from each end it is about all that can be reasonably expected on the average under all conditions of operation. This means, of course, that only 50 per cent of all such faults will be cleared simultaneously and instantaneously at both ends which is rather unsatisfactory when overall system protection is considered. The remaining sections of the line must therefore be protected by time element directional relays and again the prohibitive time feature is introduced. A redeeming feature to the scheme, however, is that a high percentage of faults outside the 50 per cent zone will cause sequential operation of the instantaneous ground relays on the two ends of the line due to the resulting increase in current after the first circuit breaker has opened. This may occur in an additional 40 to 50 per cent of possible fault locations, thus giving fairly rapid operation in about 90 or more per cent of all cases. On one installation where this scheme is used, calculations show that 50 per cent of all faults will cause simultaneous operation of the instantaneous ground relays, and sequential operation of the same relays in the remaining 50 per cent of cases. The scheme also has the practical advantage that its very rapid operation for close faults usually permits stability to be maintained on the near system, and the reduced power from the far system frequently permits that end to be cleared with a time delay without resulting in a serious disturbance.

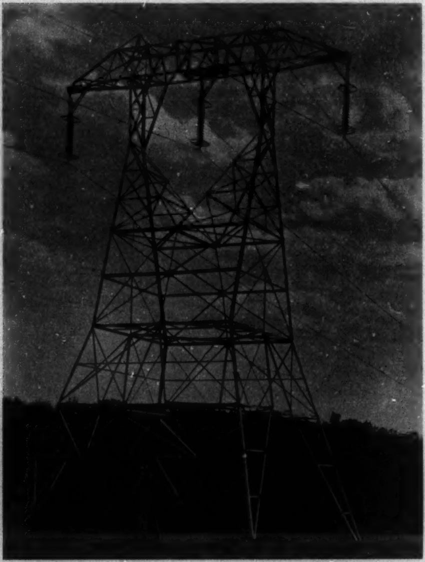


Fig. 4—Typical Tower in a Section of the Pennsylvania-New Jersey 220-Kv Interconnection

The use of distance relays for ground protection is recommended by the manufacturers and they have been installed to a limited extent in practice. Special current or voltage connections are recommended for such applications and an additional set of relays to those used for phase to phase protection is usually required. An alternative is to use one set of distance relays but to employ an auxiliary fault detector relay to change voltage connections when single-phase to ground faults occur. Reactance type distance relays would seem to lend themselves particularly to this scheme because of the possibility of varying degrees of fault resistance.

Experience with such applications seems to indicate that the complex and variable conditions present at the fault offer a wide range of quantities to the relays. This frequently results in a shifting of the balance point and changing of the power factor of the total fault circuit thus causing erratic operations of the relays for similar fault locations. Faults in the time element zones of the distance relays particularly offer problems due to changes in the fault characteristics with time. In general it cannot be said that the operation of distance relays for ground faults has been very satisfactory to date.

## CONCLUSIONS

The conclusions which may be drawn are as follows:

1. There is no standard relay scheme available today which meets all the requirements of the ideal scheme which can be universally and economically applied to the protection of open wire high voltage interconnection lines.

2. The pilot wire scheme is the only one which meets all of the engineering requirements of the ideal scheme. Recent schemes of this general type using direct current on the pilot wires have considerably improved these features and lowered the cost of this type of protection. The outstanding engineering disadvantage of this scheme is the hazard of the exposure of the pilot wires themselves. However, it is the most costly of the schemes considered and is there-

fore usually ruled out of consideration except on applications where no other scheme is possible, or where its engineering advantages may be very highly capitalized. Its future possibilities would seem to be limited.

3. The carrier current pilot relaying scheme, as at present developed, has nearly all of the engineering advantages of the pilot wire scheme and requires only terminal equipment. It has eliminated the outstanding disadvantage of the pilot wire scheme quoted above and while it cannot strictly be classed as a high speed scheme, for all practical purposes it may be so accepted. Its present outstanding disadvantage is its high cost. Its future possibilities seem very promising.

4. The distance relay scheme is a practical compromise which is usually justified because of the present adverse economics of the above schemes. Its outstanding advantages are simplicity and low cost. Its outstanding engineering disadvantages are that its total time of operation cannot be classified as high speed relaying in the usual application; and its operation for ground protection is not entirely satisfactory. Its future applications will probably be numerous by virtue of its comparatively low cost but further developments are needed to perfect this scheme, particularly for ground protection.

5. The general scheme of balanced line relaying, where possible of application, approaches closer to the pilot wire scheme than any other scheme which employs only terminal equipment. The necessity for single line protection modifies these advantages. Also separate ground relays are required. It can be readily combined with other types of relaying and its economics are very favorable. Its future applications will probably be numerous on parallel lines.

6. If the economic as well as the engineering requirements of an ideal scheme are to be considered it is evident that the following would apply: (*a*) The relay scheme shall require the installation of terminal equipment only; (*b*) The relay scheme shall compare in cost with an installation of modern directional overcurrent or directional distance relays.

## A SUGGESTED SCHEME

A perspective view of the schemes reviewed shows that any one of three schemes would meet all the ideal requirements both engineering and economic, if at least one main objection could be eliminated from each scheme. The pilot wire scheme is too expensive; the distance relay scheme is too slow; and the carrier current pilot relay scheme is both costly and somewhat slow. It therefore would appear that a theoretical solution would be to combine the desirable features of several schemes and to omit the undesirable features of all. This would seem to be accomplished by using the distance relay for speed and low cost, and extending the zone of operation of its instantaneous element by using carrier current for transferred simultaneous tripping of both terminal circuit breakers.

Therefore, neglecting cost, it is suggested that one theoretical solution of the problem would be the use of a distance relay scheme for short circuit protection, plus an instantaneous directional overcurrent relay scheme for ground protection, plus a carrier current relay scheme for simultaneously tripping the two terminal circuit breakers by the operation of any terminal relay. Such relays could be set to operate instantaneously for faults up to 60 per cent of the length of the line and thus all faults would cause at least one set of relays to operate instantaneously. The scheme of simultaneous tripping would thus cause all faults to be instantaneously and simultaneously disconnected.

It is recognized that the scheme of transferred tripping by carrier current is not yet commercially available.

## ACKNOWLEDGMENT

The constructive suggestions and criticisms by Messrs. R. N. Conwell, H. K. Sels, M. D. Hooven, L. N. Crichton, O. C. Traver, and J. H. Neher are greatly acknowledged.

## Discussion

For discussion of this paper see page 825.

# Compensating Metering in Theory and Practice

## A Practical and Economical Method of Metering High Voltage Loads From the Low Voltage Side of Power Transformers

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MEASUREMENT of high voltage energy from the low voltage side of a power transformer bank presents several advantages from both an engineering and an economic point of view. In general, the higher the voltage, the greater is the differential in cost between high and low voltage metering, and the greater is the economy if low voltage metering of the requisite accuracy can be provided.

High voltage instrument transformer equipment, especially current transformers of suitable accuracy for metering, is particularly vulnerable with respect to damage by lightning and other disturbances. This applies mainly to suburban and rural territory, while in congested districts the space required for high voltage instrument transformers is frequently at a premium.

Engineers both in the United States and abroad have given considerable thought to various methods of providing low voltage metering for measurements as of the high voltage side. The methods in use are:

1. The application of compensating devices in the meter current and voltage circuits to correct for the ratio and phase-angle characteristics of the power transformers. Complete compensation by this method is relatively complicated, and in practice the initial calibration and the periodic checking of the compensating devices are usually beyond the scope of the average meterman.

2. Adjusting low voltage meters so that their registration includes approximate increments for transformer losses.[1] This method is used to some extent in Europe, but in the United States has been confined to statistical metering. A disadvantage of the method for billing purposes is that the meter does not record the true energy that passes through it.

3. In step-down transformers, current transformers on the high voltage side with potential from the low voltage side of the power transformers; or potential transformers on the high voltage side and current from the low voltage side. The former includes core losses but omits copper losses, while the latter includes copper losses but omits core losses. Both methods give less than the true high voltage registration.

4. Compensating metering, which has been developed to provide a practical commercial method of metering of accuracy equal to that of metering on the high voltage side.

### CHARACTERISTICS OF TRANSFORMER LOSSES

Losses in power and distribution transformers commonly are divided into iron and copper losses; the general characteristics of these losses for a 7.5-kva transformer are shown in Fig. 1.

Iron losses consist of those due to magnetic hysteresis and those due to eddy currents, and are constant for constant voltage and frequency. With constant frequency, iron losses vary approximately as the square of the applied voltage; this has been verified by tests (see Fig. 2). Tests have been made also for the effect of temperature on iron losses, and this has been found negligible. Variations in frequency have an appreciable effect on iron losses; but in view of the stability of modern transmission and distribution systems, their effect is of minor importance. The tests have included also the effect of voltage variation on reactive voltamperes of the iron loss (see Fig. 2), and in different transformers this has been found to vary as $E^{3.5}$ to $E^{4.1}$, in general approaching closely to $E^4$ (where $E$ is the applied voltage).

Age may have an effect on iron loss, but this applies only to transformers constructed prior to 1915. Different manufacturers adopted non-aging silicon steel cores at different times but in general between 1905 and 1910. The present iron losses of these older transformers are generally greater than that shown by the original factory tests.

Test results of copper losses indicate that both watts and reactive voltamperes vary as the square of the load current. Because of the temperature coefficient of copper, however, these losses increase approximately 20 per cent with an increase in temperature from 25 to 75 deg C (see Fig. 1).

### PRINCIPLE OF COMPENSATING METER

Transformer losses may be measured by a meter the registration of which at all loads is in accordance with the total loss curves of Fig. 1; such a compensating meter consists of an $I^2$ element calibrated in accordance with the copper loss, and an $E^2$ element calibrated in accordance with the iron losses of the transformer. Both elements are combined on the same shaft, which drives a register of the proper ratio to record the losses in kilowatthours.

Figure 3 shows the general arrangement of a compensating meter that operates on the principle of the induction watthour meter. The lower element serves for the measurement of copper losses, and it is apparent that the currents in both the current and "voltage" coils are proportional to the load current; in the upper or iron-loss element both the voltage and "current" coils carry currents proportional to the applied voltage. The torques of the 2 elements therefore vary as $I^2$ and $E^2$, respectively, and their cumulative effect is recorded by the register.

In calibrating a meter of this type it is apparent that a definite current (for example, 5 amp) repre-

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1. For numbered references see bibliography.

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sents by design a certain speed of the disk, which in turn represents a definite copper loss in watts for a given transformer. The value in watt-seconds for one revolution then may be calculated, and the required register ratio to record in kilowatthours may be determined.[7] In practice the speed of the disk may be varied by adjusting the permanent magnets, and hence, the meter may be calibrated for use with standard register ratios (see sample calculations, Appendix *A*).

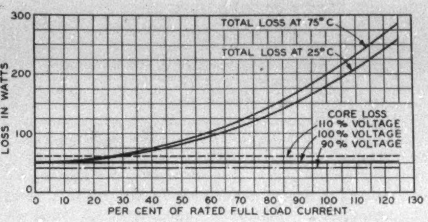


Fig. 1—Loss Characteristics of a Typical 7.5-Kva Distribution Transformer

Core losses vary approximately as the square of the voltage; copper losses as the square of the current. Effects of temperature on core loss are negligible; effects on copper loss are shown by the curves

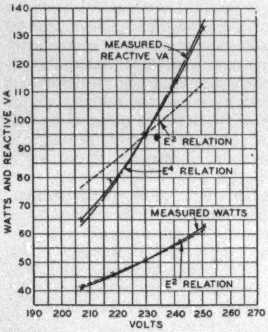


Fig. 2—Variation of Iron Losses in a 7.5-Kva Distribution Transformer

Watt losses vary nearly as the square of the voltage. Reactive-voltampere losses vary approximately as the fourth power of the voltage, and their characteristics vary slightly in different transformers

In adjusting the iron-loss element at a given voltage, the adjustable resistor is used. With no current in the copper-loss element, on the basis of the watt-second constant as determined for the copper-loss element, the upper element is adjusted for iron loss at the test voltage.

Transformer losses on polyphase circuits may be measured by applying a number of single-phase compensating meters, or the several elements may be combined into a multi-element meter as in Fig. 4. In that meter the $E^2$ and $I^2$ elements of each phase actuate the same disk.

## Accuracy Considerations

In considering the accuracy of the compensating meter, 2 conditions require consideration: (1) the effect of temperature variations of the transformer on copper loss measurement; and (2) the effect of transformer voltage regulation on iron-loss measurement. While it is possible to design compensating meters to correct for these inaccuracies, it can be shown that their effect in terms of load-plus-loss is entirely within the accuracy within which it is possible to maintain watthour meters on high voltage circuits. It should be noted that the relation of loss registration to total energy is dependent largely upon the load, and with full load on a transformer the total loss generally will be less than 2 per cent of the load. It follows that even a 10-per cent error in losses would result in only 0.2-per cent error in load-plus-loss. At no-load, when the losses represent the total high voltage load, the effect of voltage regulation is zero, and hence the iron loss measurement is accurate under this condition.

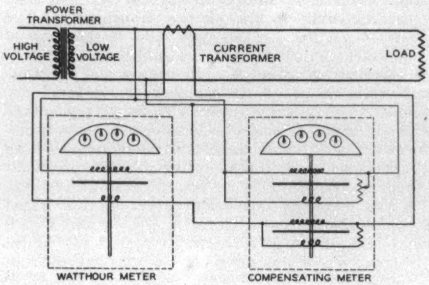


Fig. 3—Single-Phase Compensating Meter and Watthour Meter Connected on Low Voltage Side of a Power Transformer

Compensating meter consists of one $E^2$ and one $I^2$ element. The register records total losses in kilowatthours

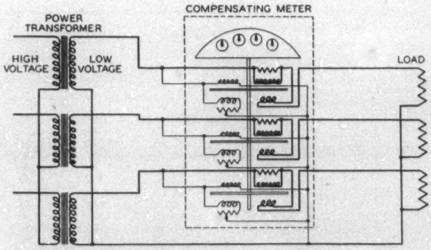


Fig. 4—Arrangement of Compensating Meter for Complete Loss Measurement on a 3-Phase 4-Wire Circuit

Meter consists of 3 combined $E^2$ and $I^2$ elements, and uses 3 disks which actuate a kilowatthour register

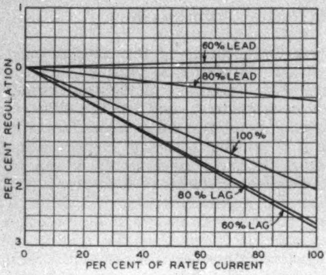
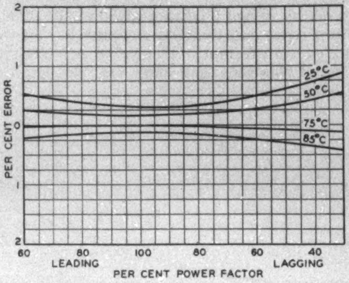


FIG. 5—(LEFT) VOLTAGE REGULATION CURVES FOR A TYPICAL 7.5-KVA DISTRIBUTION TRANSFORMER

FIG. 6—(RIGHT) EFFECT OF VOLTAGE REGULATION AND TEMPERATURE ON THE ACCURACY OF LOAD-PLUS-LOSS METERING

Curves show the maximum condition of error, which occurs with full load on the transformer; see Table I for accuracy at smaller loads



*Temperature Variation and Voltage Regulation.* The higher operating temperatures in transformers are associated with higher copper losses, and therefore it is advantageous to base the copper loss adjustment on a temperature at or near the full load operating temperature of the transformer. The 75-deg C copper loss has been used as the basis of adjustment for all calculations, tables, and tests.

The practical effect of both voltage and temperature variation has been calculated for a wide variety of conditions in Table I, which shows the percentage error in terms of load-plus-loss for a 7.5-kva transformer. In practice these errors will be less than those shown, since compensating metering generally would not be installed on transformers as small as 7.5 kva. Voltage regulation curves for the transformer considered are shown in Fig. 5, and Fig. 6 shows the accuracy performance graphically under the condition of maximum error as determined from Table I.

*High Voltage Metering Performance.* The performance of high voltage metering is of interest as a basis of comparison. Figure 7 shows typical accuracy characteristics for 2 types of meters connected to modern instrument transformers. The curves are based upon perfect adjustment of the meters, which are adjusted to correct for instrument transformer errors at the 3 setting points. Commercial tolerance generally would be of the order of ±0.5 per cent from the values shown, and therefore the actual performance obtained in service would deviate to some extent from the curves. Some variations would result also from minor differences in characteristics between different meters and instrument transformers. It should be noted that the measurement of iron loss alone, which occurs on a high voltage installation at times of no load, is only with considerable error. The exciting current of modern transformers is of the order of about 2.0 per cent of the transformer rating, at power factors that may be as low as 10 to 20 per cent. A 10- to 20-per cent error in the measurement of iron losses alone on a high voltage installation is not unusual; and in some cases iron loss alone is not measured at all, since its value is less than the starting load of the meter (see Table II, Appendix *B*).

TABLE I—EFFECT OF VOLTAGE REGULATION AND VARIATION IN OPERATING TEMPERATURE OF THE ACCURACY OF LOAD-PLUS-LOSS MEASUREMENT FOR 7.5-KVA DISTRIBUTION TRANSFORMER*

| | | Per cent error in load-plus loss measurement | | | | |
|---|---|---|---|---|---|---|
| | | Per cent power factor | | | | |
| Temp. Deg C | Per cent full-load current | 100 | 80 Lagging | 60 Lagging | 30 Lagging | 60 Leading |
| 25 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 25 | +0.05 | +0.05 | +0.07 | +0.14 | +0.13 |
| | 50 | +0.13 | +0.15 | +0.20 | +0.40 | +0.26 |
| | 75 | +0.20 | +0.24 | +0.32 | +0.63 | +0.38 |
| | 100 | +0.28 | +0.34 | +0.45 | +0.90 | +0.51 |
| 50 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 25 | +0.02 | +0.02 | +0.02 | +0.06 | +0.08 |
| | 50 | +0.07 | +0.08 | +0.10 | +0.21 | +0.16 |
| | 75 | +0.12 | +0.14 | +0.19 | +0.40 | +0.25 |
| | 100 | +0.17 | +0.20 | +0.26 | +0.52 | +0.32 |
| 75 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 25 | −0.03 | −0.04 | −0.06 | −0.10 | +0.01 |
| | 50 | −0.03 | −0.04 | −0.06 | −0.10 | +0.01 |
| | 75 | −0.03 | −0.04 | −0.06 | −0.10 | +0.01 |
| | 100 | −0.03 | −0.04 | −0.06 | −0.10 | +0.01 |
| 85 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 25 | −0.05 | −0.08 | −0.10 | −0.18 | −0.04 |
| | 50 | −0.08 | −0.11 | −0.14 | −0.26 | −0.08 |
| | 75 | −0.11 | −0.14 | −0.19 | −0.34 | −0.12 |
| | 100 | −0.13 | −0.17 | −0.23 | −0.42 | −0.15 |

* Copper-loss element adjusted on the basis of copper loss at 75°C, and core loss on the basis of no-load voltage.

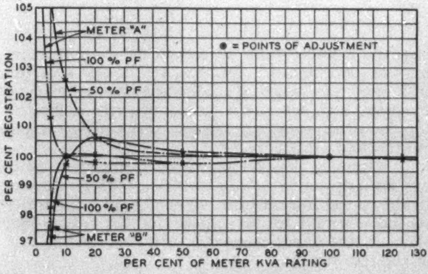


FIG. 7—CHARACTERISTICS OF 2 TYPES OF WATTHOUR METERS WITH INSTRUMENT TRANSFORMERS FOR HIGH VOLTAGE INSTALLATIONS

Curves are based upon perfect adjustment of the meters at the 3 setting points at which the meter has been compensated to correct for instrument transformer errors. Note performance at extremely light loads at low power factor, which condition exists when exciting current only is measured on a high voltage installation

## PRACTICAL APPLICATION

Consideration of the characteristics of high voltage customers' loads has made possible a practical simplification of compensating meters for such service. While theoretically, one compensating meter element is required for each transformer in a bank, the considerations discussed under "Accuracy Considerations" have made possible the development and use of a simplified form suitable for most commercial polyphase services. Such a meter consists of 2 $I^2$ elements and 1 $E^2$ element. A precaution with $\Delta$-connected transformer banks is that the impedance and reactance characteristics of the three transformers must be alike so that there may be no circulating current. This may be checked by calculation.[4] Any bank in which there is an appreciable circulating current, however, is objectionable also from the point of view of transformer operation and should be corrected. If the transformers be such that the circulating current is negligible, the 2 copper-loss elements can be calibrated for the total copper loss of the 3 transformers and the core-loss element for the total core loss of the 3 transformers. In a meter of this form, copper loss measurement is accurate for 2-phase and for 3-phase open-$\Delta$ transformer banks, and core loss measurement is exact when the voltages are balanced. For 3-phase $\Delta$-connected transformer banks the meter would be accurate for balanced load and voltage conditions. In commercial practice exact balance is rare; but as indicated under "Accuracy Considerations," an error in loss measurement of even 10 per cent becomes negligible when considered in terms of combined load-plus-loss.

As an example of an hypothetical case of an extreme condition of unbalance, a bank of 3 100-kva transformers (losses in accordance with sample calculations, Appendix *A*) may be considered as carrying a single-phase load of 100 kva at unity power factor with no load on the other 2 phases. The condition of maximum error occurs when the load is connected so that the load current flows through both copper-loss elements. Under this condition the error in loss measurement approximates +21 per cent, but in terms of load-plus-loss less than +0.4 per cent.

Conditions such as these rarely if ever would occur in practice. The errors indicated may be eliminated by providing compensating metering for each transformer. It is apparent, however, that the magnitude of these errors would not warrant the installation of the more complicated metering arrangement. This example has been cited to indicate that such load unbalance as may be expected on polyphase services would not affect the accuracy of the combined load-plus-loss measurement beyond permissible limits of tolerance, even when a lighting load is connected to one phase of a 3-phase bank.

## MEASUREMENT OF LOSS DEMAND

The maximum demand of the loss may be measured with a demand meter by providing contacts for its operation or by the addition of standard maximum demand devices. The maximum loss demand always will be coincident with the maximum load demand in kilovoltamperes, and if the load power factor be constant the loss maximum demand will be coincident with the maximum kilowatt demand. Customers' power factors, however, are not necessarily constant, and theoretically it would be possible for a customer to have a maximum kilowatt demand of 20 kw at unity power factor (20 kva) and a maximum kilovoltampere demand of 10 kw at 10 per cent power factor (100 kva). In practice, however, such conditions do not exist. Table IV in Appendix *B* shows the relation of kilowatt to kilovoltampere maximum demands of 30 typical customers' loads, together with the effect on accuracy of using the maximum loss demand instead of the simultaneous loss demand in determining the combined value for load-plus-loss. The maximum error noted was 0.14 per cent, which is entirely negligible in the commercial measurement of maximum demand. It follows that the loss increment of maximum demand may be measured by applying a watthour demand register to the compensating meter.

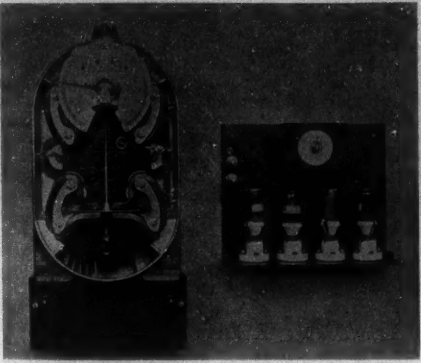


FIG. 8—A SINGLE-PHASE COMPENSATING METER SHOWING SEPARATE RESISTOR ASSEMBLY FOR CORE LOSS ELEMENT

Meter consists of one $E^2$ element and one $I^2$ element. Watthour demand register gives losses in kilowatthours and maximum loss demand in kilowatts. Resistor assembly serves for calibrating the core loss element

## MEASUREMENT OF REACTIVE KILOVOLTAMPERE-HOURS

Reactive kilovoltampere-hours of transformer losses may be measured with a compensating meter by calibrating it in accordance with the reactive kilovoltamperes of the core and copper losses. It is evident from Fig. 2 that the core-loss element should be adjusted at about the average operating voltage, since reactive voltamperes vary more nearly in accordance with the fourth power of the voltage rather than with the square as measured by the compensating meter. The error introduced into the determination of power factor is smaller than that introduced into the reactive kilovoltampere-hour measurement. For low power factors the reactive kilovoltampere-hours of the transformer losses will be a relatively small percentage of the total, while near unity power factor a much larger change in reactive kilovoltampere-hours is required for a given change in power factor. The errors introduced into the power factor determination would be within the limits of commercial tolerance except for conditions where the installed transformer capacity is much greater than the maximum demand of the load. Table V in Appendix *B* has been calculated for an assumed load factor of 25 per cent, and covers operation at several power factors for various conditions of maximum demand as related to transformer rating. It should be noted that the errors shown are for a 10-per cent difference between the actual average voltage and the voltage for which the meter was calibrated during the entire reading period. It is apparent that when the meter is calibrated at or near the true average voltage, the errors will tend to cancel.

### Calibration and Testing

The method of calibration of the compensating meter with an ammeter and a voltmeter is self-evident from the general description of the method and from the sample calculation in Appendix *A*. Service tests may be simplified by using a rotating standard operating on the principle of the single-phase compensating meter, in which case compensating meters may be tested in service by one man.

### Economics

The desirability of using a compensating meter in preference to metering on the high voltage side will depend largely upon the savings to be effected, with due consideration to all features. A compensating meter installed would cost from $150 to $200 in addition to the cost of standard metering at the low voltage. Load-plus-loss metering equipment on the low voltage side usually may be installed indoors in buildings already available; for high voltage installations, the greater cost of instrument transformer equipment, increased construction costs, the possible necessity for constructing special meter houses, or the erection of additional poles for mounting outdoor instrument transformer equipment must be considered. Savings in space and the economic value of greater safety and continuity of service, as well as a possible greater accuracy of registration, all have a tangible value. Since practices and service conditions vary in different localities, the possible economies that result from the use of compensating metering may be evaluated only by considering the particular conditions which apply.

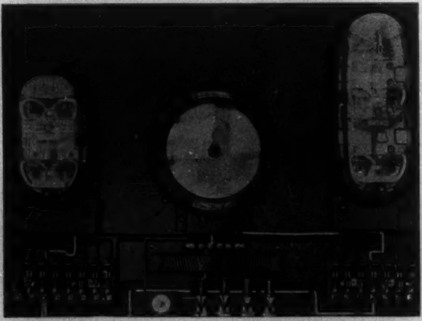


Fig. 9—Typical Polyphase Compensating Meter Panel

Includes polyphase load meter (left) simplified form of polyphase compensating meter (right) and graphic demand meter (center) with test switches and resistor assembly in lower section

### Conclusion

It is apparent that the compensating meter makes practical the measurement of high voltage energy from the low voltage side of power transformer banks, with an accuracy equal to that of high voltage metering. Under some conditions improved accuracy results; and for the measurement of energy as of a remote point on the supply lines, the method is particularly advantageous.

The cost of adding a polyphase compensating meter to a standard low voltage installation is of the order of $150 to $200, and in comparison the greater cost of instrument transformer equipment alone frequently will be much greater for the higher voltage installations. Additional savings usually will result also from the lower construction costs for low voltage as compared with high voltage metering.

In practice, there are a few cases for which the compensating meter may not prove as economical as metering on the high voltage side. Examples are: (1) customers who are supplied by a relatively large number of transformer banks, all connected to one high voltage service; and (2) customers who operate part of their equipment at the service voltage.

For the usual types of high voltage installations, either customers' billing or statistical, the application of the compensating meter will frequently result in important economies. The method is of particular advantage:

1. When the cost of load-plus-loss metering is less than that of metering on the high voltage side.
2. When the limited space available makes the installation of high voltage metering more difficult, and hence more expensive.
3. When the load conditions are such that the power transformers may be energized for considerable periods without carrying load.
4. For exposed locations on the system where ordinary high voltage instrument transformer equipment may be expected to give trouble because of lightning or other disturbances.
5. When it is desired to obtain registration as of the high voltage side to a point remote from the metering location.
6. When a customer with a rate for low voltage service and with metering already installed, is changed to a high voltage service rate.

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## Appendix A—Sample Calculations

The application of a compensating meter to a specific installation will serve to illustrate the method of determining the initial calibration both for energy and reactive kilovoltampere-hours, and for the determination of power factor as of the high voltage side, on the basis of a test on the low voltage side.

*Conditions Assumed.* A bank of 3 100-kva Δ-Δ transformers, 13,800/230 volts, supplies the total load of a high voltage customer. It is desired to measure both energy and demand as of the 13,800-volt side, using a 230-volt 800-amp meter and a compensating meter. The secondary metering equipment is connected to the power transformer secondaries by 3 1,500,000-cir mil cables, each 20 ft long.

*Calibration of Compensating Watthour Demand Meter.* The manufacturers of the transformers supplied the following data:

| Transf. No. | Core loss at rated voltage | Copper loss at full load | Per cent *IZ* drop | Per cent exciting current |
|---|---|---|---|---|
| (a) | 380 | 1,175 | 4.1 | 3.0 |
| (b) | 360 | 1,165 | 4.05 | 2.8 |
| (c) | 372 | 1,171 | 4.1 | 2.9 |

Total core loss at 13,800 volts = 380 + 360 + 372 = 1,112 watts ........ (1)

Total copper loss at full load on power transformers (753.1 amp secondary) = 1,175 + 1,165 + 1,171 = 3,511 watts ........ (2)

Using 800-amp current transformers, copper loss at full load on current transformers (5-amp secondary) =

$$\frac{800^2}{753.1^2} \times 3{,}511 = 3{,}962 \text{ watts} \qquad (3)$$

Copper loss in cables ($I^2R$) =

$$\frac{800^2 \times 0.0072 \text{ ohms} \times 20 \times 3}{1{,}000} = 276 \text{ watts} \qquad (4)$$

Total copper loss at 800 amp = 3,962 + 276 = 4,238 watts ........ (5)

The compensating meter as supplied makes one revolution in 3.6 sec with 5 amp in the current circuit (both $I^2$ elements). To calibrate the compensating meter to read in kilowatthours, the normal watt-second constant would be

$K_s$ = 4,238 × 3.6 = 15,256.8 watt-seconds per revolution of the disk ........ (6)

To use a standard register, it is necessary to have a standard watt-second constant. By referring to the manufacturers' table of standard registers and constants, the watt-second constants closest to that desired are 17,280 and 12,960. Either of these watt-second constants may be used, and the choice may properly be made by selecting the one for which the demand scale of the watthour demand register provides sufficient overload capacity in relation to the full load losses.

Total losses at 800 amp (Items 1 and 5) =
(380 + 360 + 372) + (3,962 + 276) = 5,350 watts ........ (7)

Assume the use of a standard watthour demand register with a scale of 10.2 kw, a gear ratio of 2,777-7/9, operating with a watt-second constant of 12,960. (Register constant = 1.) The copper loss elements then must be recalibrated for a speed faster than 3.6 sec per revolution.

Required seconds per revolution =

$$\frac{K_s}{\text{Total Copper Loss}} = \frac{12{,}960}{4{,}238} = 3.058 \text{ sec} \qquad (8)$$

The core loss element then must be calibrated so that at 230 volts its torque will be equivalent to 1,112 watts.

Seconds per revolution at 230 volts =

$$\frac{K_s}{\text{Total Core Loss}} = \frac{12{,}960}{1{,}112} = 11.655 \text{ sec} \qquad (9)$$

For tests in service at other voltages, 225 volts for example:

$$\text{seconds per revolution} = \frac{230^2}{225^2} \times 11.655 = 12.178 \text{ sec} \qquad (10)$$

*Calibration for Compensating Reactive Kilovoltampere-Hour Meter.* If it be necessary to measure average monthly power factor, a standard reactive voltampere-hour meter may be used on the low voltage side, and a compensating meter added for reactive kilovoltampere-hours of the power transformer bank.

The procedure is the same as for the watthour meter, except that the calibration of the elements is based on the reactive instead of the energy components of the losses. The required reactive voltampere values are calculated from the data of the transformers. The remaining calculations are the same as for the energy loss meter, substituting reactive voltampere values for watts. The constants of the reactive meter usually will be different from those of the watthour meter for the same transformer bank.

For the installation under consideration, the following results are obtained from these calculations:

$$\left.\begin{array}{ll}
\text{Total reactive voltamperes of core loss at 230 volts} & = 8{,}629 \\
\text{Total reactive voltamperes of load loss at 800 amp} & = 13{,}243 \\
\text{Watt-second constant } (K_s) & = 43{,}200 \\
\text{Seconds per revolution for copper-loss element at 5 amp secondary (800 primary)} & = 3.262 \\
\text{Seconds per revolution for iron-loss element at 230 volts} & = 5.006 \\
\text{Gear ratio } (R_g) & = 8{,}333\text{–}1/3 \\
\text{Register constant } (K_r) & = 10
\end{array}\right\} \quad (11)$$

Reactive compensating meters should be calibrated at approximately the average operating voltage. (See Fig. 2 for characteristics of reactive voltamperes of core loss.)

*Calculation for Power Factor Obtained by Test.* If power factor be obtained by test (as for example, with indicating instruments) tests made on the low voltage side may serve as a basis for calculating power factor as of the high voltage side. For the installation under consideration, it is assumed that a power factor test on the low voltage side shows a load of 200 kw at 80 per cent power factor at 225 volts.

With this method the values determined for energy and reactive voltamperes of both core and load losses, in accordance with Items 1, 5, and 11, are supplied to the power factor tester.

The service calculations are as follows:

$$\text{Line current} = \frac{200{,}000}{0.80 \times 225 \times \sqrt{3}} = 641.5 \text{ amp} \qquad (12)$$

$$\text{Watts copper loss} = \frac{641.5^2 \times 4{,}238}{800^2} = 2{,}725 \qquad (13)$$

$$\text{Watts iron loss} = \frac{225^2 \times 1{,}112}{230^2} = 1{,}064 \qquad (14)$$

Reactive voltamperes of load loss

$$= \frac{641.5^2 \times 13{,}243}{800^2} = 8{,}515 \qquad (15)$$

Reactive voltamperes of core loss

$$= \frac{225^4 \times 8{,}629}{230^4} = 7{,}904 \qquad (16)$$

Coördinating these values with the test results:

| Load | Kw | Reactive kva | Kva | Per cent power factor |
|---|---|---|---|---|
| Low Voltage | 200.00 | 150.00 | 250.00 | 80.0 |
| Iron Loss | 1.06 | 7.90 | | |
| Copper Loss | 2.73 | 8.52 | | |
| High Voltage | 203.79 | 166.42 | 263.00 | 77.5 |

## Appendix B—Test Data of Performance Under Various Conditions

*Comparative Results for a Service Installation.* This test was made in an office building supplied from 2 2,300-volt 2-phase 3-wire services, each connected to a bank of 2 250-kva 2,300:115/230-volt transformers. Either bank may carry the lighting or the power load, and in case of emergency both loads may be supplied from a single bank. Results of these tests are given in Table II.

*Comparative Results for a Test Installation.* Two 7.5-kva 2,300/230-volt distribution transformers were connected to transform from 230 volts to 2,300 and back to 230. Identical meters were connected to the input and output sides, and a compensating meter, adjusted for the losses of the transformers, was connected to the output side. The tests included a wide variety of load and power-factor conditions over a relatively short period of time; the results are given in Table III.

TABLE V—PER CENT ERROR IN REACTIVE KILOVOLTAMPERE-HOUR MEASUREMENT AND ITS EFFECT ON POWER FACTOR FOR DIFFERENCES IN APPLIED VOLTAGE FROM CALIBRATED VOLTAGE FOR THE ENTIRE READING PERIOD

Based on: assumed load factor of 25 per cent; 3 100-kva transformers in accordance with sample calculation Appendix *A*

| Maximum kva demand in % of transf. rating | Load power factor | Per cent difference in reactive kva-hr | | | Difference in % power factor | | |
|---|---|---|---|---|---|---|---|
| | | Actual avg. voltage in % of calibration voltage | | | | | |
| | | 90 | 100 | 110 | 90 | 100 | 110 |
| 100 | 100 | +11.9 | 0 | −12.9 | −0.29 | 0 | +0.55 |
| | 86.6 | + 2.8 | 0 | − 3.9 | −0.81 | 0 | +1.24 |
| | 70.7 | + 2.0 | 0 | − 2.9 | −0.76 | 0 | +1.15 |
| | 50 | + 1.5 | 0 | − 2.3 | −0.50 | 0 | +0.79 |
| 75 | 100 | +15.4 | 0 | −14.6 | −0.40 | 0 | +0.82 |
| | 86.6 | + 3.7 | 0 | − 5.0 | −1.08 | 0 | +1.60 |
| | 70.7 | + 2.7 | 0 | − 3.8 | −1.02 | 0 | +1.49 |
| | 50 | + 2.1 | 0 | − 3.1 | −0.72 | 0 | +1.06 |
| 50 | 100 | +19.9 | 0 | −16.0 | −0.70 | 0 | +1.56 |
| | 86.6 | + 5.4 | 0 | − 6.7 | −1.61 | 0 | +2.35 |
| | 70.7 | + 4.0 | 0 | − 5.0 | −1.52 | 0 | +2.10 |
| | 50 | + 3.2 | 0 | − 4.4 | −1.09 | 0 | +1.52 |
| 25 | 100 | +24.0 | 0 | −17.0 | −2.08 | 0 | +4.09 |
| | 86.6 | + 8.9 | 0 | − 9.8 | −2.91 | 0 | +3.89 |
| | 70.7 | + 7.3 | 0 | − 8.3 | −2.71 | 0 | +3.25 |
| | 50 | + 6.1 | 0 | − 7.3 | −2.08 | 0 | +2.25 |

It should be noted that the table shows extreme conditions of error since it assumes differences between calibration and actual average voltage of 10 per cent *for the entire period of the reading.* When a true average voltage is used for the calibration test of the reactive kilovoltampere-hour meter, the errors will tend to cancel.

TABLE II—COMPARISON OF MEASURED INPUT, OUTPUT, AND LOSS KILOWATTHOURS ON 2 250-KVA 2,300:115/230-VOLT TRANSFORMERS

| Elapsed time (days) | Interim kilowatthours | | | | | | Per cent differences between reading dates | |
|---|---|---|---|---|---|---|---|---|
| | Input billing meter (polyphase) | Input test meters (single-phase) | Output meters | Loss | | Output-plus-loss | From input billing meter | From input test meters |
| | | | | A phase | C phase | | | |
| | Installed—Connected to power load (Approximate power factor = 75%) | | | | | | | |
| 10 | 10,060 | 10,110 | 9,533 | 297.16 | 286.63 | 10,116.79 | +0.56 | +0.07 |
| 10 | Meters tested | | | | | | | |
| 21 | 8,330 | 8,360 | 7,770 | 294.76 | 289.72 | 8,354.48 | +0.29 | −0.06 |
| 30 | 7,100 | 7,120 | 6,580 | 261.03 | 254.76 | 7,095.79 | −0.06 | −0.34 |
| 40 | 6,580 | 6,570 | 5,987 | 292.71 | 289.13 | 6,568.84 | −0.17 | −0.02 |
| 50 | 7,000 | 7,040 | 6,440 | 294.54 | 288.51 | 7,023.05 | +0.33 | −0.24 |
| Total power | 39,070 | 39,200 | 36,310 | 1,440.2 | 1,408.75 | 39,158.95 | +0.23 | −0.10 |
| | Meters tested | | | | | | | |
| | Connected to lighting load (A-phase only) C-phase loss meter removed for tests in laboratory (see Table III) | | | | | | | |
| 4 | | 6,780 | 6,617 | 141.39 | | 6,758.39 | | −0.32 |
| 4 | Service oil switch opened for construction work | | | | | | | |
| 15 | Service oil switch closed—no load | | | | | | | |
| 21 | | 0* | 0 | 178.97 | | 178.97 | | +100.0* |
| 21 | Secondary load switch closed | | | | | | | |
| 28 | | 9,020 | 8,815 | 227.48 | | 9,042.48 | | +0.25 |
| 35 | | 10,600 | 10,372 | 239.46 | | 10,611.46 | | +0.11 |
| 42 | | 11,950 | 11,638 | 251.75 | | 11,889.75 | | −0.50 |
| 49 | | 9,910 | 9,634 | 232.45 | | 9,866.45 | | −0.44 |
| 56 | | 8,570 | 8,348 | 218.56 | | 8,566.56 | | −0.04 |
| 63 | | 11,150 | 10,882 | 245.93 | | 11,127.93 | | −0.20 |
| 70 | | 10,400 | 10,162 | 235.33 | | 10,398.33 | | −0.02 |
| 77 | | 3,460 | 3,373 | 72.79 | | 3,445.79 | | −0.40 |
| Total A-phase light | | 81,840 | 79,841 | 2,044.11 | | 81,886.11 | | +0.06 |
| Combined light and power | | 121,040 | 116,151 | 3,484.31 | 1,408.75 | 121,044.06 | | +0.003 |

* Input test meter did not register since core loss is less than the starting load of the meter (1,104 watts = 0.48 per cent of meter rating).

(+) signs indicate that output-plus-loss is greater than input registration.

(−) signs indicate that output-plus-loss is less than input registration.

TABLE III—COMPARISON OF MEASURED INPUT, OUTPUT, AND LOSS KILOWATTHOURS FOR TESTS ON 2 7.5-KVA TRANSFORMERS UNDER VARIOUS LOAD CONDITIONS

(230/2,300–2,300/230-volt connection, single-phase load)

| Per cent load on power transf. | Per cent load on input meter | Per cent power factor (input) | Per cent load factor (output) | | Duration of test (hours) | Measured output kwhr | Measured loss kwhr | Measured output-plus-loss kwhr | Measured input kwhr | Per cent difference between input kwhr and output-plus-loss kwhr | Possible accuracy of reading registers (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.0 | 35.0 | | | 187 | 0 | 21.038 | 21.038 | 20.975 | +0.31 | ±0.7 |
| 0<br>100 | 1.0<br>66.0 | 35.0<br>99.1 | 8.33 | 22<br>2 | 24 | 14.527 | 3.208 | 17.735 | 17.625 | +0.625 | ±0.6 |
| 0<br>100 | 1.0<br>66.0 | 35.0<br>99.1 | 33.3 | 16<br>8 | 24 | 59.587 | 5.005 | 64.592 | 64.635 | −0.068 | ±0.15 |
| 0<br>100 | 1.0<br>66.0 | 35.0<br>99.1 | 50.0 | 16<br>16 | 32 | 119.122 | 8.372 | 127.494 | 127.57 | −0.056 | ±0.065 |
| 100 | 66.0 | 99.1 | 100 | | 16 | 119.071 | 6.735 | 125.806 | 125.87 | −0.052 | ±0.066 |
| 25 | 17.3 | 98.6 | 100 | | 16 | 53.701 | 2.137 | 55.838 | 55.95 | −0.2 | ±0.183 |
| 15.9 | 11.4 | 25.5 | 100 | | 17 | 18.454 | 3.968 | 22.422 | 22.375 | +0.21 | ±0.49 |
| 43.8 | 29.6 | 79.0 | 100 | | 16 | 50.301 | 3.042 | 53.343 | 53.450 | −0.2 | ±0.19 |
| 71.2 | 47.5 | 89.0 | 100 | | 15 | 75.023 | 4.138 | 79.161 | 79.35 | −0.24 | ±0.13 |
| 58.5 | 39.2 | 99.0 | 100 | | 24 | 98.052 | 4.762 | 102.814 | 102.75 | +0.062 | ±0.10 |
| 51.7 | 34.8 | 85.0 | 100 | | 15.5 | 55.100 | 2.998 | 58.098 | 58.25 | −0.26 | ±0.18 |
| 8.9 | 6.7 | 25.0 | 100 | | 17 | 10.129 | 2.510 | 12.639 | 12.55 | +0.71 | ±0.90 |
| 7.3 | 5.7 | 24.5 | 100 | | 64 | 33.405 | 9.023 | 42.428 | 42.275 | +0.36 | ±0.30 |
| 21.2 | 15.0 | 46.8 | 100 | | 21 | 43.592 | 3.210 | 46.802 | 46.80 | +0.004 | ±0.22 |
| Combined | | | | | 314 | 750.064 | 80.146 | 830.210 | 830.425 | −0.03 | ±0.006 |

(+) indicates that output-plus-loss is greater than input registration.
(−) indicates that output-plus-loss is less than input registration.

TABLE IV—LOAD CHARACTERISTICS OF 30 TYPICAL CUSTOMERS' LOADS SHOWING ACCURACY OF A WATTHOUR DEMAND REGISTER FOR MEASURING THE LOSS INCREMENT OF THE MAXIMUM KILOWATT DEMAND

| Customer No. | Business class | Measured maximum kw demand | Measured kva at time of maximum kw demand | Per cent power factor at time of maximum kw demand | Measured maximum kva demand | Per cent error in indicated loss demand** | Per cent error in indicated load-plus-loss demand |
|---|---|---|---|---|---|---|---|
| 1 | Shipbuilding* | 1,875.0 | 2,180.0 | 85.9 | 2,180.0 | 0 | 0 |
| 2 | Pressed steel specialties* | 1,720.0 | 2,450.0 | 70.2 | 2,450.0 | 0 | 0 |
| 3 | Chemical manufacturer* | 1,500.0 | 1,705.0 | 87.9 | 1,725.0 | +1.72 | +0.048 |
| 4 | Tire manufacturer* | 1,368.0 | 1,547.0 | 88.3 | 1,547.0 | 0 | 0 |
| 5 | Wool products* | 1,300.0 | 1,424.0 | 91.2 | 1,424.0 | 0 | 0 |
| 6 | Steel construction* | 1,200.0 | 1,434.0 | 83.6 | 1,434.0 | 0 | 0 |
| 7 | Textile mill | 1,150.0 | 1,490.0 | 77.2 | 1,530.0 | +3.90 | +0.126 |
| 8 | Sand and gravel* | 1,040.0 | 1,145.0 | 90.8 | 1,145.0 | 0 | 0 |
| 9 | Gear works* | 800.0 | 895.9 | 89.3 | 895.9 | 0 | 0 |
| 10 | Paper manufacturer* | 672.0 | 736.0 | 91.2 | 736.0 | 0 | 0 |
| 11 | Brick manufacturer* | 552.0 | 552.6 | 99.9 | 552.6 | 0 | 0 |
| 12 | Steel foundry* | 515.0 | 566.0 | 91.0 | 566.0 | 0 | 0 |
| 13 | Quarry | 508.0 | 592.1 | 85.9 | 592.1 | 0 | 0 |
| 14 | Lime quarry* | 360.0 | 390.0 | 92.3 | 390.0 | 0 | 0 |
| 15 | Steel tubing manufacturer* | 163.5 | 182.5 | 89.5 | 182.5 | 0 | 0 |
| 16 | Hosiery mill | 160.0 | 181.6 | 88.1 | 182.2 | +0.53 | +0.015 |
| 17 | Building material | 147.3 | 226.0 | 65.2 | 226.0 | 0 | 0 |
| 18 | Ice plant* | 130.4 | 142.5 | 91.5 | 143.2 | +0.75 | +0.020 |
| 19 | Textile mill | 112.0 | 162.0 | 69.1 | 167.0 | +3.99 | +0.144 |
| 20 | Sand and gravel | 109.0 | 135.2 | 80.6 | 136.1 | +0.97 | +0.030 |
| 21 | Conduit manufacturer | 96.0 | 110.5 | 86.8 | 110.5 | 0 | 0 |
| 22 | Hosiery mill* | 79.6 | 92.3 | 86.2 | 92.3 | 0 | 0 |
| 23 | Car repair shop* | 64.8 | 68.7 | 94.5 | 68.7 | 0 | 0 |
| 24 | Aircraft plant | 63.6 | 89.6 | 71.0 | 89.6 | 0 | 0 |
| 25 | Dairy | 59.3 | 65.1 | 91.2 | 65.1 | 0 | 0 |
| 26 | Steel construction* | 57.6 | 64.4 | 89.4 | 64.4 | 0 | 0 |
| 27 | Office building | 54.8 | 75.0 | 73.2 | 75.0 | 0 | 0 |
| 28 | Laundry | 47.0 | 58.8 | 79.9 | 58.8 | 0 | 0 |
| 29 | Signal service | 43.2 | 52.3 | 82.5 | 53.3 | +2.78 | +0.083 |
| 30 | Waste manufacturer | 31.2 | 37.2 | 83.8 | 37.2 | 0 | 0 |

* These customers have power-factor corrective equipment.
** Loss demand in kw is considered to be 2.5 per cent of measured maximum kva demand. At the time of maximum kva demand, losses are taken to consist of 25 per cent core loss and 75 per cent copper loss.
(+) indicates that the loss maximum demand plus load maximum demand is greater than the load maximum demand plus the coincident loss demand.

## Discussion

For discussion of this paper see page 829.

# Discussion

## TESTING OF HIGH SPEED DISTANCE RELAYS

(GEORGE—see page 802)

**R. C. Buell:** Actual tests of relays under system operating conditions provide the most reliable assurance of the proper functioning of this protective equipment. However, the fact that the relays have previously operated, or subsequently operate correctly once during a staged test, does not prove conclusively to a skeptical operating force that their operation was correct during a particular system disturbance. Careful analysis of all relay operation during system disturbances may disclose any erratic operation of such devices. However, in making any such analysis the relay engineer has been greatly hampered in the past by the lack of accurate data showing current and voltage magnitudes, and sequence of breaker operation. The only accurate method available for obtaining information actually to check relay operation during system disturbances is by the use of an automatic oscillograph, which always is ready to record the actual quantities that cause the operation of the relays.

The writer believes staged tests are expensive. Can Mr. George give us some idea of the cost of staging a relay test on a 110-kv circuit? It is the writer's belief that the elimination of the necessity of just one such stage test would justify the use of an automatic oscillograph that would be available to check constantly the proper operation of relay equipment. An example is cited in the following:

Only 3 of the 4 oil circuit breakers of a double-circuit, 110-kv line involved in a double circuit fault opened, the fourth failed to open, but after three seconds the fault cleared. Did the relays on the fourth breaker function incorrectly? The automatic oscillograph record showed that due to high fault resistance, the current was too low to operate the single line back up protection provided for this circuit. With this positive information provided by the oscillograph the relay engineer immediately turned his attention to the design of a more effective method of protecting this line, rather than to test in an endeavor to find out what happened.

**H. R. Huntley:** In the third item of the suggested program for staged tests, Mr. George mentions cooperation with the communication organizations in cases where ground faults are to be placed on power transmission lines in connection with relay testing. Cooperation between the power and communication people is, of course, particularly helpful in situations where there may be inductive coordination problems, since in such cases, data of value from the standpoint of coordination may often be obtained at much less expense than would otherwise be involved. Also, as Mr. George points out, data obtainable by the communication people may, in some cases, be of value from the standpoint of power system operation.

**M. S. Schneider:** Mr. E. E. George states that no satisfactory method has been developed for placing a temporary fault on a hot transmission line.

A very satisfactory method for placing artificial faults on energized transmission lines has been used by the Union Gas and Electric Company. It consists of three pieces of pipe supported on pillar insulators, with a bar arranged on a pivot so that when released by a solenoid and trigger arrangement it will fall across these pipes by gravity. The cross bar is insulated from the control circuit by an insulating link. The solenoid can be operated by portable batteries, or most any source of supply. The device is easily dissembled for transportation and can be set up and adjusted in a short time. It has been used very successfully at voltages up to 132 kv and could be extended to higher voltages without difficulty.

In low-voltage testing of any relays, and in particular distance relays, special emphasis should be placed on the wave form of current and voltage as this may have considerable effect on their calibrations. It is not sufficient that the impressed voltage be sinusoidal as the iron present in relay circuits usually will distort the current wave considerably unless precautions are taken. This distorted current may have considerable effect not only on the relay but also on the indicating instruments.

Mr. E. E. George has not emphasized the importance of minimum wipe of contacts on bouncing of relay elements. Many otherwise mysterious incorrect relay operations can be found to have been due to this effect. If this type of operation is found, adjustments can easily be made to correct it.

In distance relays the coordination in timing between the various elements of the relay is very important for correct performance. The writer agrees with the author that the most satisfactory way to determine this is by staged primary testing, as this takes all factors into account, and no assumption need be made. We have found for our system that the best time to make these tests is during heavy load conditions, as the system disturbance is less than at light load periods. The system set up can be changed, or as is usually done, current limiting devices can be used to obtain the required current.

The writer can testify to the value of the automatic oscillograph in analyzing the performance of relays since we had one of these devices installed on our system for a considerable length of time. One instance in which a supposedly incorrect operation was found to be correct after analyzing the record of the automatic oscillograph is given in the following paragraph.

During a severe lightning storm all four 66-kv circuits connecting the Columbia generating station of the Union Gas and Electric Company with the Hartwell-Terminal substation relayed, but only 3 of them operated at both ends. At first this appeared to be an incorrect operation but a careful analysis of the oscillograph record showed that faults had occurred on only the 3 lines which had opened at both ends. The fourth one was opened at the generating station by the excessive load current. Another interesting and valuable conclusion drawn from this record was that, although these faults had appeared to be simultaneous, they occurred several seconds apart. Also, the first two faults were on circuits on separate double circuit lines. It may be that other seemingly simultaneous faults were separate faults.

Nevertheless, even though the automatic oscillograph is a valuable aid to the relay engineer, it can not take the place of staged tests, which will give information on relay performance under a large number of different conditions in a short space of time.

**H. W. Smith:** In any distance relay application it is desirable to know by how much the ratio of the current transformers breaks down under conditions of maximum short circuit at certain locations.

As staged tests usually are made with less than maximum short-circuit currents in order to avoid excessive system disturbance, they do not usually develop conditions which give the maximum ratio change in current transformers; when this is the case it is necessary still to determine the maximum ratio change by other means and to allow for it.

It should be borne in mind that, in general, current transformer ratio change under short-circuit conditions is much more pronounced on 25-cycle than on 60-cycle systems.

In the application of distance relays of impedance type to underground cable systems where conductor resistance is equal to or predominates over reactance, the quantity to be measured by the relays may change to the order of 10 per cent on account of resistance variations due to temperature. This is a factor that is not taken care of automatically by a staged test and which must be allowed for.

**A. R. van C. Warrington:** Mr. George has made several valuable criticisms and suggestions concerning the improvement of testing instructions provided by manufacturers of distance relays. The only suggestion that is difficult to follow concerns staged testing. Detailed instructions are not given by the manufacturer because the few customers who employ this excellent method have widely differing ways of carrying it out, and because of the great variation in individual system connections. The subject is beyond the scope of a relay instruction book, but it has been very ably covered by this paper, which represents the first practical treatise on it.

Under the heading of "Equipment Used in Testing," a phase shifter is listed as well as a reactor. While a phase shifter and phase angle meter are useful for taking low voltage characteristics of the directional units of impedance and reactance relays in the laboratory (to detect current bias) yet in routine testing of these relays, a tapped 10-ohm resistor is sufficient to check the main characteristics of either type of relay. In the instructions on the reactance relay, the current through the relay is limited by a variable resistance and a tapped resistance in series. To simulate the sudden change from load to fault conditions, the resistor is short-circuited and the current is now limited by the reactor representing a dead fault. Similarly, by cutting out only part of the resistance, an arcing fault can be simulated.

Although laboratory checks are necessary, we wish to emphasize the value of initial system tests, which are the surest method of setting distance relays since they check the overall characteristics of the line, current transformers, potential transformers, and relays.

**E. E. George:** The value of automatic oscillographic equipment on the power system has been well presented by Mr. R. C. Buell but it is preferred to regard such equipment as a desirable supplement and not as a substitute for staged tests.

Mr. M. S. Schneider's device for placing a temporary fault on a hot transmission line should be of great value. Most of the devices known by the writer have not been thoroughly satisfactory or reasonably cheap and convenient. Mr. Schneider's comments about adjusting relay contacts are of great importance and his statement is endorsed without qualification. Considerable difficulty has been caused in the past by too much contact wipe. Solid silver contacts are supposed to eliminate this difficulty.

The cost of staged tests is small, perhaps because most of the men involved normally are on a monthly salary. Transportation of men involves some direct cost and occasionally linemen are required to assist in preparing for and carrying out the tests. In general the direct cost of staged tests is insignificant. The total direct and indirect costs of a 2-day program of 15 or 20 staged tests would seldom be over $300. The real value of a staged test is in the number of questions it answers and the number of problems it solves,—compared to any other means of obtaining these answers or solutions, whether they are obtained by tedious "paper and pencil" methods, flippant "cut and try" methods, or pathetic "wait and hope" methods.

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## RELAYING OF HIGH VOLTAGE INTERCONNECTION TRANSMISSION LINES

(Sleeper—see page 808)

**H. D. Braley:** The writer discusses particularly the part that system stability has taken in the protective field. As pointed out by Mr. Sleeper it is now recognized that in relaying of large capacity high voltage lines stability is a major consideration in their protection. In fact it is the chief factor which has led to the development of high speed breakers and relays.

It may be gathered from statements made in the paper that the relaying features have not been entirely solved. Distance relays in combination with carrier current are suggested as means of securing instantaneous tripping for the entire length of circuit. It appears doubtful however, that distance relays ever will offer a complete solution even when used in combination with carrier current control. It is clear that any distance relay which is located at or near the reactance center of the system may be subject to low or actually zero voltage during severe surging or out-of-step conditions. As system connections are changed due to lines being out of service or changes in connected generating capacity the reactance center, or electrical neutral, also will shift.

Under some conditions therefore the lines may be tripped out at one point and for other conditions at another point. The disadvantages of these are, of course, apparent. A suggested amendment therefore is offered to the 4th item of the "Requirements of the Ideal Relay Scheme" to the effect that in case the systems lose synchronism the relays should operate to effect the separation at a preferred point only.

The schemes using transferred tripping or carrier control all use standard types of relays that are controlled in their tripping operation by the current and voltage conditions prevailing at the line terminals. If they are subject to incorrect operation during abnormal line conditions when *not* so controlled it may be correctly inferred that they are not entirely free from faulty operation when controlled by pilot wires. In this respect they differ from the true pilot wire scheme wherein the two currents at the terminal points are directly compared. It may also be pertinent to recall that with carrier control, the signal which governs the tripping is initiated at any instant by the relays at only one end of the line.

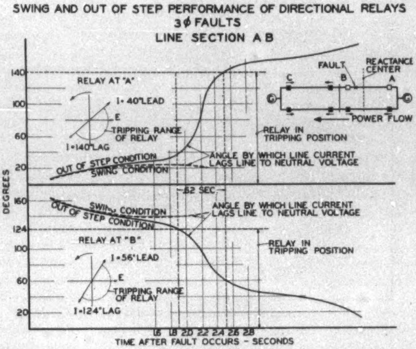

Fig. 1

It has already been indicated that distance relays may give improper operations. This also is true of wattmeter type directional elements used with both distance and overcurrent relays. That such conditions can prevail is rather clearly indicated by Figs. 1 and 2 which show the results of calculations made on an actual system of the type under discussion.

Fig. 1 shows the angular position of line current with respect to line-to-neutral voltage, plotted against time as it would appear to the directional relays. The small vector diagram at the left shows the operating range of a directional relay. One line in section *AB* of the transmission line is assumed to have tripped out as a result of a three-phase fault. The dotted curve shows the angular relations when the power flow previous to the fault was just within the stable power limit and the full line the conditions when the power flow was just above the stable limit.

It will be observed that the relays at the two ends of the line are in the tripping range for 0.62 seconds which would be more than sufficient time for high speed relays to trip out the remaining circuit. Further calculations show that if the power transmitted just prior to the fault had been 20 per cent greater the time interval for tripping the relays would be reduced approximately 75 per cent. This time interval also will become smaller and smaller on succeeding swings. It may be noted that the reactance center of this system is near station $B$ for this particular operating set up.

Fig. 2 shows the conditions that exist on the next section of the line. In this section the time interval for tripping the relays is but 0.04 seconds. The chances of the relays tripping on this section are therefore reduced almost to the vanishing point. The operating angle of the relays on section $BC$ has been purposely shifted to reduce the probability of tripping under out-of-step conditions in order to eliminate dropping load at substation $B$.

One of the selling points for distance relays has been that they would eliminate the necessity for extensive calculations to determine the proper setting of relays. This has not proved to be in accord with the facts. Not only is it necessary to make extensive fault calculations but in addition studies of transient power swings in the case of long high voltage circuits also are essential if the requirements of complete protection are to be fully understood and satisfied.

It may be that extensive work of this nature will not always be required. If the ideal relay scheme is devised certainly it should no longer be necessary.

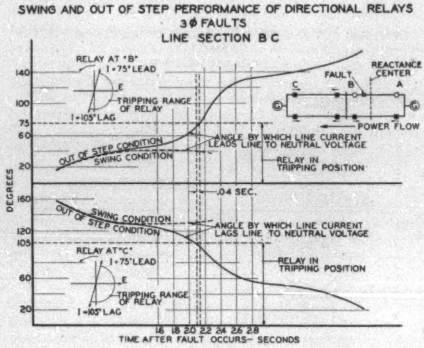

Fig. 2

**L. N. Crichton:** This subject is covered in such great detail from all points of view of technical requirements that the conclusions must be considered authoritative. Many relay engineers might disagree with some of the details, but such small disagreements cannot change the conclusions. The particular advantage of the scheme which Mr. Sleeper suggests in his closing paragraph is that it is always workable, even if the carrier should fail. Incidentally, the equipment for this type of installation is obtainable.

But what of the economics of this scheme? The distance relays will clear the majority of line troubles instantaneously from both ends of the section. In the minority of cases, where the trouble is near one end, that end will be cleared very fast. The reactance of the line will, on many systems, materially reduce the shock to the system while the sequential clearing is taking place. A further point is that if the system is not always operating under full conditions instability will result due to sequential operation. But even if a perfect relay system is provided, there are sure to be some failures of service. There is the occasional catastrophe, and there is the more frequent trouble in some lightning districts where more than one section of line is grounded either by the same lightning stroke or by several strokes separated by a short interval of time. If this occurs in such a way that all the ties are interrupted, the systems will be separated. It, therefore, appears possible that on many systems the expenditure for the carrier current to provide the additional last fraction of protection may not give sufficient return to justify itself. If this last refinement in protection could secure absolutely continuous service, it might be justified; whereas if it reduces the total yearly failures from, say, 2 interruptions to, say, 1 of the unavoidable ones just mentioned, it might not be considered justifiable. Such an economic study based on the actual interruption records of several typical systems is something that is urgently needed.

**E. Ettlinger:** The paper emphasizes the improvements in relaying that can be secured through the use of pilot wire methods, either using direct current or power line carrier channels, in situations where, due to the complexity of the network requirements for speed, etc., such methods can economically be justified.

In the last sentence of conclusion No. 2, the author indicates that future possibilities of pilot wire relaying seem to be limited, based upon economic considerations. It is my observation that channels for pilot wire service may be leased in some parts of the country from the Bell System at rates that are substantially lower than those for voice communication. On the basis of such rates there seems to be a greater chance for economic justification than appears in the paper.

It has been my privilege recently to review the performance record of a pilot wire relaying system operated by the Oklahoma Gas and Electric Company in one of its divisions where, due to the importance of certain types of load, rapid relaying was required, which previously had not been obtainable, because of the nature of the transmission network. A pilot wire relaying scheme employing leased Bell System lines for a distance of approximately 20 miles was installed initially in 1930, and later extended to involve some 150 to 200 miles of transmission system. After the initial difficulties that are common to a new application had been eliminated in the first few months of operation, very satisfactory results were obtained and the operators are highly satisfied with the service rendered. An indicating type of instrument was used continuously to indicate the condition of the leased wire circuit and experience indicated that although some discontinuities have occurred, they have not interfered with power line relaying.

It is the writer's opinion that with the rates that may be found available for leased wire service in various parts of the Bell System, in connection with pilot wire relaying, that specific study of situations is warranted to determine the economies of pilot wire relaying *versus* carrier current pilot relaying where other methods of relaying are not adequate.

**S. L. Goldsborough:** The idea of compelling a distance relay to continue to indicate according to its original interpretation is entirely feasible and can be carried to considerable advantage in some cases. The feature cannot be secured by any type of seal-in-device but rather must be accomplished by giving the distance elements a low resetting value. In all cases where the opening of the breaker restores full voltage to all relays responding to current through that particular breaker, the reset value can be made extremely low thus accommodating large values of arc resistance. However, in the case of parallel lines or similar conditions, a low reset cannot be tolerated because it is necessary that the distance elements reset on an ohm value only about 20 to 30 per cent greater than the value involved during the original interpretation. This idea can therefore only be applied to considerable advantage on applications where the breaker opening immediately produces normal voltage on the distance element.

It does not appear quite logical to use the fictitious average time of distance schemes for comparison purposes. From the standpoint of stability in the numerous cases where it is saved by the high speed clearing of one end of the line, it appears to be more correct to say the distance relay scheme is a high speed scheme for all faults.

**E. M. Hunter and E. H. Bancker:** This paper is a very fitting sequel to Mr. Neher's *Use of Communication Facilities in*

*Transmission Line Relaying*[1] in summarizing the recent developments and present state of the protective art. It is noteworthy that attention is turning once more to one of the oldest and most nearly ideal forms of relaying, namely, pilot protection. As the author states, it has suffered from two disadvantages, the necessity for providing some other form of backup protection, and the cost and maintenance of the pilot conductors. That the first is not a great deterrent is evidenced by the almost universal use of the analagous differential protection for generators and transformers of any size. It has therefore been because of cost that pilot protection is in such limited use.

The renewed interest in the pilot forms of relaying may be directly ascribed to the rising cost of other types of protection not depending upon time as the basis of selectivity. In other words the pilot scheme has been considered the ideal but to avoid its cost, recourse was had to less expensive and less effective forms of relaying. As the need and desire for better protection arose the cost of the substitutes began to approach that of the best, so that now the disparity is often slight when the costs of the entire installation are compared.

The writers agree thoroughly with the author's last sentences under the subjects "Pilot Wire Relaying" and "Carrier Current Pilot Relaying." It is our opinion that when all of the factors are taken into consideration some form of pilot relaying can economically be justified on practically every important interconnection between large systems. This especially is true of systems operating near the stability limit, since pilot relaying is more easily rendered insensitive or immune to oscillations than any type of distance relay.

The characteristics exhibited by a severely oscillating or unstable system deviate only a trifle from those obtaining during short circuits and differ from each other by a very small amount. The protective relays are required to operate for faults, must not operate for swings, and may or may not be required to operate during instability depending upon individual preference of users. Since distance relays are surveying instruments that utilize the electrical dimensions of the system at their location, they are presented with a very difficult problem of discrimination in attempting to distinguish between faults, swings, and instability. In an impedance relay the discrimination between normal and abnormal conditions usually is performed by the impedance devices. In a reactance relay it must be performed by a starting fault detecting unit and not by the reactance elements. This is so because except during faults, reactance elements always will measure the distance to that point of the system where unity power factor exists, and as this must invariably be in the instantaneous zone of some relay, it would clear at once if allowed to do so. The comparison of the relative susceptibility of impedance and reactance relays to system swings, must therefore be made between the impedance elements and the starting element of the reactance relay and not directly between the distance measuring elements. This is too involved a story for treatment in this discussion, and it is the writers' intention to present it more fully in the near future.

While the writers are in agreement with the author with respect to the economic superiority of the newer forms of pilot relaying, the limitations of these newer forms must not be overlooked if satisfactory results are to be obtained. In the earlier types of pilot protection a direct comparison was made between the magnitude, phase angle, or both, of samples of current from each end of each conductor of a circuit. Any dissimilarity was evidence of an internal fault and indicated immediate action by the relays to disconnect the line. In the newer types all of the conductors comprising a circuit are treated as a unit, the conditions at each end are translated into relay contact position, and the result telegraphed to the other end via a pilot or carrier circuit. If, as is customary, a single telegraph channel is used, only one indication can be transmitted with regard to the conditions at each end. When the relays are acted upon by two opposing factors, such as fault and swing currents or two simultaneous faults in different lines, the more potent will prevail and the result may be a delay in tripping. Furthermore a pilot system based upon the use of circuit rather than conductor conditions is not inherently insensitive to the currents arising from swings and instability. It is however, possible by proper design to prevent such a system from unnecessarily tripping lines during instability or to arrange it so that only the line spanning the electrical center will clear, whichever is desired. When a split at a predetermined point is required the pilot system may be arranged to be inoperative for unstable conditions and a separate out-of-step relay used to separate the unstable sections at the desired geographical point.

The writers do not agree with the author that the suggested scheme of using distance relays with transferred tripping via carrier, incorporates the good features of several systems and omits the undesirable features of all. It would be no more secure against incorrect tripping during swings than the distance relays. The trip impulse would not reach the remote end whenever the conductors used as a carrier channel are short-circuited. Therefore for the most severe faults, the three-phase ones, the schemes would not provide fast tripping. It is recognized that some improvement in reliability would be obtained if the trip impulse were sent over another circuit such as another line or an actual pilot wire but any carrier pilot system that uses the line itself as a channel should only do so when it is not at fault. In other words, carrier should be used only as a blocking medium for external faults and the clearing of internal faults which may involve the carrier channel should be independent of carrier operation.

The use of the automatic oscillograph for recording system disturbances cannot be too highly recommended. A record of the magnitude and phase relations of the currents and voltages at a relay station during a disturbance shows the number of phases and whether or not ground was involved in the fault and eliminates all guesswork as to the cause of the relay operation. It is not always possible to stage short-circuit tests to check relay settings and the need for such tests is reduced if a record is obtained of system disturbances as they occur.

**E. E. George:** The requirements of the ideal relay scheme have been presented by Mr. Sleeper very adequately and it seems doubtful if many engineers would suggest any important modifications in such requirements at the present time. When it comes to the relative advantages and disadvantages of the various schemes, opinion is likely to be shaded by operating experience and various engineers will have their preferences based on experience and local conditions. While we agree almost entirely with everything in Mr. Sleeper's paper there are a few points that suggest discussion.

*Distance Relays.* For instance, we feel that no serious delay is introduced in a reactance type relay by the operation of the fault detector element or starting unit. This unit replaces the directional unit of the impedance relay and is fast, even in the original type of distance relay. The time of operation is only a few cycles at ordinary operating currents and naturally still less on heavy short circuits. Newer designs have rendered this time negligible. While it is true that the reactance measuring or ohm unit will tend to operate during out-of-step conditions and other extreme surges, the starting unit has practically the reverse characteristic (made possible by shifting the phase angle of pick up), so that coordinated action of the two elements is necessary for tripping. This inherently requires that the pick-up and dropout values of the starting unit should be very close together, as has been brought out in the discussion by Messrs. E. M. Hunter and E. H. Bancker. Most of the improvement in distance relay design and application since the original development has been due to improvements in the art of coordinating the starting and reactance measuring of the relay. In the writer's opinion it is possible to give almost ideal protection either to long or short lines with reactance type distance relays. In general, operation on out-of-step conditions can be controlled to a satisfactory degree and these relays are now operating satisfactorily on many extensive interconnections which formerly presented very difficult relay problems.

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[1] A.I.E.E. Trans., June 1933, p. 595.

Some readers may question the statement that distance relays are relatively inexpensive. While the relays themselves are costly compared to overload relays, they require very little in the way of major equipment changes, instrument transformer changes, or auxiliary circuits. Therefore the overall installation and maintenance costs of distance relay schemes are relatively low, especially in view of the freedom from limitations on line design and operating procedure common to previous types of protection.

*Pilot Wire Relays.* It is encouraging to see the inherent advantages of pilot wire protection brought out so clearly in Mr. Sleeper's paper.

One new factor in favor of pilot wire relaying has just appeared. It appears that one of the large communication companies is now willing to make a distinction in its rate schedule between leased *control* circuits and leased *communication* circuits by offering a much lower rate for the former class of service. This seems logical since the control circuits do not have any traffic expense and are not chargeable with the advantage of tying in with a world-wide communication network. The enormous undeveloped field for pilot wire protection will tend to make the use of pilot wire protection more or less inversely dependent upon the unit cost. Capital cost can be changed to an operating cost by the use of leased circuits. If the rates for leased pilot wire service are lowered sufficiently and if the protective and maintenance practices now imposed by the communication companies are modified to suit the power companies' requirements as they may develop from time to time, it seems probable that no other scheme of protection known at the present time could hope to compete with pilot wire in the near future for transmission line protection.

Perhaps, a combination of distance relays and leased pilot wire circuits may combine the advantages and eliminate the disadvantages of the two schemes, since certain distance relays provide an adequate initiating unit for the pilot wire and also give back-up protection in case of pilot wire failure.

**J. H. Neher:** Mr. Sleeper is to be congratulated on his excellent presentation and summary of the advantages and disadvantages of the various methods available for relaying interconnection transmission lines. The writer comments on his suggested theoretical solution of the problem, which consists, in effect, of distance short-circuit and instantaneous overcurrent ground protection applied to each end of the line, supplemented by a "transferred tripping" arrangement of the carrier current type in order to obtain instantaneous tripping over the entire line length. The objection is, of course, the high cost of the supplementary transferred tripping feature; and this cost is chargeable only to the speeding up of the tripping on 30 per cent of the line.

Considering the transferred tripping feature separately as a supplement rather than as a component part of the scheme, this part of the problem involves merely the ability to transmit at all times a distinguishable signal instantly from one line end to the other in either direction. Simultaneous signal transmission in both directions is not required. Since it is probable that facilities for some form of telephonic communication already are provided between the stations terminating the line, I reiterate the statement made in my paper to which Mr. Sleeper has referred, *i.e.*, that the logical means of transmitting this signal is over the communication system already installed. Although certain difficulties suggest themselves, particularly when the communication lines are leased, and when they pass through switchboards, nevertheless, these difficulties are not insurmountable, and I believe that when they can be overcome, this will result in a lower cost for the transferred tripping feature than if a carrier current communication channel were installed solely for the purpose.

Where the selectivity of the relay protective scheme is not dependent upon the reliability of the signal transmission, some sacrifices in the reliability of the communication channel may be made in order to justify economically the addition of the transferred tripping feature. The possibility of incorrect tripping due to false signals may be minimized by making the receivers receptive only when their associated distance relays are endeavoring to operate in one of their several zones.

**O. C. Traver:** Mr. Sleeper's paper details definitely the absolute need of prompt action in the clearing of faults. This coincides with the manufacturers' ideas, but it is probably more convincing to operating men, coming as it does from one of them. It is only to be expected that there will be a difference in opinion concerning the relative effectiveness of the various means for accomplishing this result, which is a minor consideration once we are conscious of the value of speed.

Mr. Sleeper points toward a speed goal which, though seemingly distant, is considered by us as designers to be not only attainable but surpassable. Probably none of the methods described in this paper has reached its limit of speed. Distinct improvements have been made while the paper was being printed. More are in sight. In fact, if one were to plot a curve showing the average delay in selective relay timing against each of the past ten years, the result would be startling.

There is, clearly, some misunderstanding concerning the purported limitation of reactance relays to short line applications, as stated in the paper. In general, the longer the line, the easier it is to protect with distance relays, whether of the impedance or the reactance type. The fact that some maximum length of line for the average case may have been assumed, is no barrier to caring for a longer line, if encountered. This capability of operating on both short and long lines is peculiar to a first power action such as inherently exists in a reactance relay. It is an outstanding advantage of the reactance relay as compared to the second power performance of impedance relays.

Though distance relays have not, as yet, been much used for ground faults, it is chiefly a question of economics. Methods of overcoming this handicap will be announced at a subsequent meeting.

While it is inherently true that any distance relay tends toward unnecessary operation under system oscillating conditions, we cannot agree that the impedance type is superior from this standpoint. In the case of the reactance relay with which the writer is concerned, the starting unit requires, at unity power factor, nearly four times its reactive setting to function. This is the chief control during surges. The suggested use of the original measurement to determine the time for operation of an impedance relay would be more hopeful if we did not need to consider the conditions directly following the clearing of the fault. System oscillations, for example, may have progressed sufficiently to continue an action and cause faulty tripping.

The only criticism offered in the paper to carrier-current pilot protection is one of speed and this frankly not as an objection to its use, but simply because it does not come up to the high theoretical standard. On the other hand, it comes nearer to that goal submitted by Mr. Sleeper than any other practical method for the average trunk line. We may well add that for tapped lines, the carrier method stands in a class by itself.

The operating time for the carrier pilot has not reached bottom. It probably will not be long before it will meet this standard also. It is not good engineering policy to attempt to reach the ultimate at once.

For parallel line protection I consider the balanced current relay preferable to balanced power wherever the former is applicable (and it usually is) because of the faster action and the freedom from potential connections.

The suggested scheme at the close of the paper is one of considerable promise though not quite new, having been described in the Gross U. S. Patent No. 1,849,830. Until means have been devised to insure passing carrier through a fault, the blocking method will be preferable.

It appears, therefore, that all of Mr. Sleeper's difficult requirements will, in time, be met excepting possibly the one of cost. In general, cost will follow the general rule of varying with value and this will be inversely as the reduction in time. This tendency toward increase will, on the other hand, be tempered as usual by the effects of quantities and experience.

**W. E. Winterhalter:** Mr. Sleeper has given a comprehensive outline of problems which, as interconnection loading increases, impose new demands on equipment for system protection.

The near future will find substantial progress toward realization of some of the characteristics specified for ideal protection of interconnections. More inherent selection, a close approach to simultaneous isolation of both terminals of sections, less susceptibility to indiscriminate operation during oscillation between systems, and adaptation to clearance of phase and ground faults, are outstanding features of the most recently developed carrier current pilot wire protection. Impedance and reactance relays as applied to protection of interconnections do not, at present, show any promise of meeting these requirements to the same degree, but substantial improvements in the direction of decreased operating time without incurring unreliable operation on moderate swinging between systems, can be expected to increase their usefulness.

Observation of one type each of impedance and reactance distance relays on several unstable interconnections has shown that both are subject to indiscriminate operation in about the same degree during violent swinging between systems. Such operations invariably occurred at sectionalizing points closest to the electrical center of the interconnection.

The reactance relay in question is somewhat different from either type described by Mr. Sleeper; its assembly consisting of a starting element, a reactance ohmmeter and a d-c operated timer. Installations requiring overall distance measurements up to 14 ohms secondary reactance, from relay to distant fault locations, have been in service for several years without experiencing tripping under normal peak loads having 18 to 16 ohms secondary impedance and the usual range of load power factors. This is made possible by features incorporated in the starting element, the two principal ones being its adjustment to have maximum torque at large angles of lag (between 45 and 75 degrees), and a potential circuit which limits current variation in the "volt-ampere operating element" voltage coil to a ratio of 10 to 1, for a variation of primary voltage between 100 per cent and 1 per cent.

Neglect to specify or adjust (when more than one adjustment is provided) directional elements having an angle of maximum torque corresponding closely to the average power factor angle of short circuit currents is, with all directional relays, a major source of disappointing results such as incorrect directional indication, slow, and insensitive operation.

The most desirable field for impedance and reactance relays appears to be in protection of interconnections that are reasonably rigid and wherein reactance relays, not having objectionable features outlined by Mr. Sleeper, are more generally applicable since the variable resistance component of impedance is eliminated in their ohmmeter distance measurements. Experience up to the present time would indicate that pilot wire protection should be given preference where investigation shows that systems or sections of systems are subject to violent oscillation and cannot maintain synchronism if heavy faults are not cleared within 0.2 to 0.3 seconds.

A fair comparison of costs for relay and auxiliary equipments, exclusive of breakers and potential and current transformers or devices, would be 12 to 15 per cent for the directional overcurrent type, 25 to 40 per cent for the impedance or reactance types, and 100 per cent for carrier current pilot wire equipment. Each type mentioned has a definite application on present day systems and in considering their qualifications to protect service and equipment, each is least expensive in its legitimate field.

The problem of maintaining system stability during disturbances has been given the conspicuous place it deserves as a primary factor dictating speed requirements of relays and breakers. In its solution, an additional demand, distinctly separated from required functions of earlier relays and breakers is incurred. From an economy standpoint it would seem that due credit should be given a protective system that will contribute substantially to this end when comparing it with one of limited value in this respect.

Considerable caution must be exercised in the use of bushing current transformers, bushing potential devices, and low voltage potential transformers. The low ratio bushing type current transformer has a very limited burden capacity and also a low impedance secondary, comparable to, or less than, that of low current rated induction overcurrent ground relays. The bushing potential devices have not in every case proved satisfactory for energizing impedance and reactance relays. The use of low voltage potential transformers may introduce complications in selecting suitable adjustments of impedance or reactance relays where interconnections are long, and terminal transformer impedance or reactance may be that of several banks.

**H. P. Sleeper:** Several have disagreed with my conclusion that the future for pilot wire relay protection in this country is apt to be limited. It appears to me that this is solely a question of economics. If this scheme proves to be the cheapest to permit the simultaneous tripping of terminal circuit breakers it will be certain to be used. If as Mr. Neher suggests the same circuits can be used for telephone communication it would certainly seem that present costs can be improved where separate circuits are now required for the two functions. Also the attitude of the communication companies is interesting where special rates are offered for leased circuits used for relay work only. I still feel that the best scheme inherently and theoretically is some system which is self-contained in the high tension transmission system and at the moment this brings us logically to some system of carrier current transmission.

If, as some of the manufacturers have commented, it is impossible at present to transmit a carrier impulse over a faulted high tension circuit it would seem to point out clearly the opportunity for research work. The present scheme of using the blocking system, rather than the direct tripping system, of carrier current relaying appears to me to be fundamentally wrong. It immediately imposes a necessary interval of time selection while the blocking relays are operating, and greatly increases the probability of incorrect relay operations due to the fact that all circuits passing fault current must have a correct relay operation in order that only the defective section will trip. The direct tripping scheme avoids this and in addition should enable faster operation to be secured. The engineering solution of this problem does not seem to be insurmountable since its equivalent has already been accomplished in high frequency wire telegraphy where the ground return system enables impulses to be transmitted over a broken wire.

## COMPENSATING METERING THEORY AND PRACTICE

(Schleicher—see page 816)

**A. Boyajian:** The scheme outlined by Mr. Schleicher is very attractive but unfortunately its field of application appears somewhat limited:

1. It is applicable only to the total load of a transformer and not to individual customers or feeders.

2. Three and four winding transformers complicate it to such an extent as to greatly reduce or eliminate the economy of the scheme.

3. Tap changing, especially if automatic, makes the loss measurements of doubtful approximation.

4. Twenty per cent difference between the hot and cold impedance losses and the wide variation of core loss exponent with voltage in different transformers may become an appreciable item in some cases, for instance, when power flows in both directions as in an interconnection.

5. It requires the consent of the customer or public utility commission.

6. The equipment cannot be certified to by a testing bureau except by field tests at a great expense.

7. As each case has to be an individual tailor made job, most of the economy may vanish if all the engineering expenses involved are fully charged against it.

8. Any litigation on the accuracy of billing could not be defended with any scheme other than high voltage metering.

It may be significant to note that other low voltage metering schemes of even greater economy and accuracy than the one outlined by Mr. Schleicher have found very limited use: for instance, the scheme with a single watthour meter and a series line drop compensator for impedance loss and shunt compensation for core loss, capable of approximating the variation of the losses with temperature and voltage very closely. The reason again must be that each job has to be tailor made, cannot be calibrated and certified to by itself, and engineering and verification expenses are very high.

Certainly, schemes of this character may be used by mutual agreement, but, from the standpoint of engineering accuracy, none can compare with the modern high voltage instrument transformers.

**Stanley Green:** This paper is of interest because it has possibilities for making a measurement that fundamentally the watthour meter with its instrument transformers is not able to accomplish adequately even if installed on the primary side of a transformer installation.

Watthour meters always have been an accurate class of instrument and within the last few years have been made to be dependable on unity power factor within one-half of 1 per cent between load values of from 5 per cent of nominal rating to 300 per cent of nominal rating. This accuracy is expressed in terms of actual energy measured rather than in per cent of nominal rating and marks the watthour meter as an accurate instrument over a singularly wide range of loads. But even this really is of no avail in measuring the core losses of transformer banks. The accuracy of the best modern watthour meters below 5 per cent of full load current and at extremely low power factors is an unexplored region and results obtained in this region will change, not only because of unavoidable variations in friction, but because of inherent design characteristics that vary in different types of meters. It is doubtful whether commercially it is desirable to attempt any further improvement of meters below the 5 per cent load point on extremely low power factors.

In the case of core losses of transformers, it is just this range of operation to which the watthour meter and its current transformers are subjected. These fixed losses are of an entirely different order of magnitude than the main load current as far as their existence at any given instant is concerned, yet because they go on constantly it is not unusual to see their integrated importance assume the same order of magnitude as that of the load energy. This creates a difficult measuring situation and one which it is expecting entirely too much of the watthour meter to cover. Mr. Schleicher has pointed out this in connection with the watthour meter accuracy curves he has given in Fig. 7. The situation may be summarized by saying that when primary metering is installed, a large element of uncertainty is introduced under a condition where the load energy is small and the transformer bank is large.

Although the author of the paper has intimated that his method may be used for billing metering, its application for statistical metering also, should not be overlooked. In the case of far-flung power systems with large numbers of substation transformers, it may be beneficial to have loss metering, in order better to allocate energy distribution of the power system. An inherent advantage of the method from a statistical standpoint is that it segregates the actual transformer losses from the useful energy passing through the transformer and in this way calls attention to undesirable conditions, if they exist.

**Paul MacGahan:** The problem of metering power as supplied at high voltage involves the question of avoiding the expense of high voltage current and potential transformers, as well as that of the errors of transformation. The latter generally is conceded to be relatively unimportant in modern instrument transformers, and, therefore, Mr. Schleicher's paper probably is of interest more particularly from the cost standpoint.

The paper leaves the impression that the method described is entirely new, and mention is made of a patent application covering the "compensating meter." As a matter of record, it should be pointed out that this method of metering high tension power is not new. Meter engineers have been familiar with the scheme of separately metering the power transformer losses and adding the result to the low-tension metering readings to obtain the high voltage power delivered. An article by L. J. Lunas in the *Electric Journal*, April, 1929, p. 180, describes this method quite fully, as well as other methods. Furthermore, the Siemens-Schuckert Company of Germany has circulars describing the method and listing the necessary transformer loss meters for sale.

The question, therefore, follows as to why there has been no previous demand in America for the application of this system. In the writer's opinion, this may be due to the application difficulties involved, particularly in determining the proper calibration to suit each separate installation, and in proving out the correctness of the result in a way that would be satisfactory to the consumer and to the Public Service Commissions.

**W. H. Pratt:** The novelty of the method proposed in this paper is not in the idea of adding loss measurements to secondary output, or of basing these loss measurements on values of current squared and voltage squared, but rather in combining in a single meter the measurement of the two types of losses. Descriptions of measurements of primary power based on the use of three meters, a watthour meter, a current-squared hour meter and a volt-squared hour meter are of numerous years' standing.

A drawback of the method is that a calibration of the power transformers is involved and the application of the method seems limited to those cases where the whole output of a transformer bank is used by the customer. There are other limitations also. It is questioned, if when account is taken of all the preparatory calibration and adjustment, whether most of the economies expected do not disappear.

In the recent past, there has been so much reluctance to use the somewhat special meter structures that are required when two-stage meters are employed, that it is somewhat surprising to find this equally complicated metering method advocated.

The final tabulation of the appendix bears out a contention that has been maintained for a good many years by the writer, that the power factor of loads at the time of maximum demand will be found within a rather narrow range. This has a bearing on the choice of simple forms of kilovoltampere meters when used for determining the kilovoltampere of maximum demand.

**G. B. Schleicher:** The compensating meter has been developed primarily to meet a very definite need in the field of high voltage metering equipment. By far the great majority of high voltage metering installations are installed on customer's premises, and in this field the compensating meter already has demonstrated its advantages in providing for the simplification of the high tension receiving equipment, for improved accuracy, and for increased reliability both in operation and in registration.

Experience has demonstrated that the accuracy is equal or better than for metering on the high voltage side, and that the required calculations and the calibration of compensating meters can be performed by metermen (not engineers) in accordance with an established routine.

In regard to Mr. Boyajian's points:

1. When a transformer supplies more than one customer, there is no commercial need for high voltage metering, and hence neither high voltage metering nor compensating metering is used commercially for this purpose.

2, 3. Multiwinding and automatic tap-changing transformers are always of large size, and are rarely if ever used on customer's premises. Compensating metering can frequently be applied, but either for high voltage or for compensating metering each case of this type should receive individual consideration to determine the most economical method.

4. Table I and Fig. 6 show the effect of both temperature variation and voltage regulation to be well within the accuracy that can be maintained by a watthour meter on the high-voltage side. Their effect, therefore, is of negligible importance in the combined measurement of load-plus-loss.

5, 6, 8. Public utility regulatory bodies undoubtedly will welcome the improved accuracy and greater reliability of compensating metering, and the verification of an installation seems relatively simple. The major part of the load is measured by an ordinary watthour meter; the compensating meter may be tested with equal facility, and the transformer losses are easily verified from the manufacturer. And even a considerable error in losses could hardly affect the overall accuracy to the extent of bringing it outside of commercial limits. (See "Practical Application," in the paper.)

Customers also welcome compensating metering. In one case a customer who has no load at night now opens his primary oil switch and saves core losses. In another instance, a customer has disconnected one transformer in an under-loaded delta bank and thus operates more efficiently. Both are the direct result of installing compensating metering which has served as an index to inefficient operation.

7. There is nothing "tailor-made" about a routine compensating meter installation. The manufacturer of the transformer supplies the loss data, and the calculation and initial calibration of the compensating meter takes a meterman (not an engineer) about the same time as a comparable watthour meter.

The line-drop compensator scheme, which Mr. Boyajian considers superior, has several important disadvantages. These are immediately apparent to metermen:

1. The burdens imposed on instrument transformer secondaries are high, which adversely affects the accuracy of registration, not only of the loss but of the entire load.

2. The compensating device operates on the load meter, which reduces its reliability and the certainty of its correct operation.

3. The testing of the line-drop compensator is outside of the scope of metermen, and when compensation for temperature is added, such a test becomes an engineering problem.

It is for these reasons undoubtedly that the line-drop compensator method has not found favor in metering practice.

Mr. Green indicates the desirability of extending the use of compensating metering also to statistical purposes. Undoubtedly there is a large field for the meter in this direction, because even in efficient transformer arrangements for conditions of maximum load, the loss over a period of time frequently represents a surprisingly large percentage.

Mr. MacGahan questions the originality of the method of metering as here proposed, and I concur to the extent that the addition of *calculated* $E^2$ and $I^2$ components to the low-tension load is probably as old as transformers themselves, but the combined *measurement* of the losses in kilowatt-hours in a single meter is new.

Mr. Lunas' article (bibliography 11 in the paper) describes two methods of metering; one is a combination of methods (1) and (3) listed in the introduction of the paper, and the other uses *separate* $E^2$ and $I^2$ hour meters together with a watthour meter on the low-tension side. Incidentally, Fig. 4 of Mr. Lunas' article gives an indication of the magnitude of the burdens that the line-drop compensator method may impose on current transformers. Such burdens are too high for accurate metering connected to standard current transformers.

The bulletin of Siemens-Schuckert* and the second method described by Mr. Lunas are identical, and possess the commercial disadvantage of introducing ampere-square-hours, volt-square-hours, and odd multipliers, which undoubtedly would prove rather mystifying to non-technical customers. The compensating meter, while utilizing the same principles, combines the loss measurement into a single reading in "kilowatt-hours," with which customers are already familiar.

The bulletin of Siemens-Schuckert also answers Mr. Boyajian's question with reference to the exponent of the core loss, by stating in direct translation: "In adding to the readings of the watthour meter on the low-tension side the loss kilowatt-hour obtained from the $E^2$ and $I^2$ meters, one obtains the same number of kilowatt-hours as by measurement on the high-tension side." This is true within the practical limits of accuracy at which meters may be maintained.

Mr. Pratt recognizes the novelty of the compensating meter, but speaks of the *calibration* of the power transformers. It should be noted that the power transformers are not calibrated as instrument transformers are calibrated, because compensating metering uses only the loss data which the transformer manufacturers already have available.

Experience has definitely indicated the practicability and simplicity of the method. Its use provides not only for economies, but also for the simplification of the high tension structure, greater reliability of operation, improved accuracy, and the freedom from fault disturbances which contributes to continuity of service.

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*Zahler zur Bestimmung der Leerlauf- und Kupferverluste der Leistungstransformatoren," Siemens-Schuckert (Germany) *Bulletin No.* 1615/5.

# Interrupting Capacity Tests on Circuit Breakers

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TESTS of many kinds are necessary to establish the rating and check the performance of an oil circuit breaker. For many of these tests, such as insulation and heating, the apparatus required is commonly available, while the technique of making the tests is well known and the analysis of the results presents no unusual problem. Equipment for making interrupting capacity tests on a large scale has not been generally available. Even though much has been published on these tests, there still seems to be some uncertainty of the correctness of certain testing schemes and possibly some question of the ability of even large laboratories to make tests that definitely establish the ratings of breakers of the larger interrupting capacities now being manufactured. So much interest has recently developed on this phase of oil circuit breaker testing, that it seems desirable to give a general discussion of the many variables in equipment, procedure, and interpretation of results.

This paper is presented in connection with the investigation of the entire subject of factory and field testing of circuit breakers now being carried out under the auspices of the Switching and Switchgear Committee of the Association of Edison Illuminating Companies. It is thus a part of what it is hoped will eventually be a complete literature on the subject and is preliminary to the report which will be brought out by that committee at a later date and which will treat more exhaustively many of the same subjects covered in this paper.

## EQUIPMENT

Although numerous interrupting tests have been made in the field, the number of such tests is small compared with those made in laboratories. The equipment of an adequate laboratory,[1] in addition to especially designed generators, reactors, and transformers, must include such other apparatus as follows:

MAJOR AUXILIARY MEASURING AND INDICATING EQUIPMENT

| Apparatus | Use |
|---|---|
| Magnetic oscillograph | Records currents, tripping impulse, voltage, contact speed and travel, and pressure |
| Cathode ray oscillograph | Records recovery voltage characteristics |
| Travel recorder | Provides record of contact travel, contact parting, and speed for recording on magnetic oscillogram |
| Pressure recorder | Provides record of pressure at various places in breaker, such as above oil and below oil, for recording on oscillogram |
| Ballistic wattmeter | Records arc energy during interruption |

## PROCEDURE

Interrupting capacity ratings of circuit breakers are given in terms of the voltage of the system on which the circuit breaker may be applied and the current or kilovoltamperes which the breaker may be called upon to interrupt, the current being measured at the time of contact separation. There are, however, many additional points which must be considered if assurance is to be had from a series of tests that a breaker is capable of performing its rated duty under any conditions that may exist in practise. The considerations which are involved, the extent to which these considerations influence the significance of laboratory tests, and the steps taken by testing engineers to assure reliable tests are discussed under separate headings below.

## CO *versus* OCO TESTS

The present standard interrupting duty cycle[2] specifies that the interrupting rating of an oil circuit breaker be based on two OCO operations (close on a short circuit and trip). In laboratory tests, particularly on breakers whose fundamental design has been reasonably well established, the OCO tests are used.

It has been found, however, that the CO cycle (trip from the closed position) is very useful in the development of new designs of interrupting schemes. The reason for this is that the CO operation eliminates many variables and produces simpler records from which pressure, speed, arc duration, and other data pertinent to an understanding of the breaker performance are readily determined. Also, it is desirable in many cases to take advantage of the higher short-circuit currents made available by pre-tripping, that is, setting the trip mechanism in motion before the short circuit is thrown on. The CO cycle lends itself more readily to this practise than does the OCO cycle. After satisfactory performance is indicated from the CO tests, OCO tests are made.

The difference in duty resulting from OCO tests compared with CO tests is that in establishing the short circuit during OCO tests, arcing occurs which produces some pressure and contact burning. On poorly designed breakers, particularly those of flimsy construction or with inadequate or improperly designed mechanisms and opening springs, the OCO test may result in unusual stress on the breaker compared with the CO test. On the other hand, by a proper design of such parts as contacts and mechanisms, the arcing on closing during OCO tests can be so reduced that the OCO test is but little more severe than the CO test. In a few respects, the OCO cycle is less severe than the CO cycle, particularly when the tripping is so rapid that the breaker does not

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[1] For detailed description of apparatus and its arrangement, see "High Power Interrupting Testing Station," by G. F. Davis, *Gen. Elec. Rev.*, February, 1932.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

[2] A.I.E.E. Standard 19-107.

close completely. Burning on the primary contacts may be eliminated in these cases, for instance, and excessive opening speed may be avoided.

### PRE-TRIPPING

Pre-tripping means that the inherent delay in the tripping and parting of the breaker contacts after the short circuit is applied is eliminated by giving a trip impulse before the short circuit is applied. The principal advantage of this procedure is that the interruption can be started while the generator short-circuit current is near its maximum. Thus greater use is made of the output of the generator. Many schemes are used for pre-tripping. Most of them are satisfactory, there being no one that is outstanding in its advantages.

The use of pre-tripping is considered entirely legitimate in breaker testing. It has been questioned primarily on two counts, namely that interruption may occur while the short-circuit current is very much offset and therefore is easier to accomplish and also that higher than actual current interrupted may be indicated. From the discussion of these items in another section of the paper, it may be seen that their relation to the interrupting duty is well understood and can readily be interpreted.

Although pre-tripping on OCO tests is possible, it is not generally recommended because it may require the breaker to operate in a way not required in service and not contemplated in the design and so give very misleading results.

### EFFECT OF FREQUENCY

On the older types of plain-break breakers where the arc duration was long, the results of interrupting tests at 60 cycles and 25 cycles were generally about the same. On the more modern types of breakers, however, particularly those of the oil-blast type which on low voltages have normal arc durations of not more than a cycle, frequency may have a very decided effect on the breaker performance, the duty being more severe at 25 cycles. The reason for this is that normally the arc will be extinguished at the first current zero. On 60 cycles the first current zero will appear sooner than at 25 cycles so the arc length on 60 cycles, and likewise the duty, is less. Breakers have sufficient factor of safety, however, so that even though tested at 60 cycles, they will meet their full rating when used on 25 cycles.

### POWER FACTOR

It has been frequently stated that as the phase angle between current and voltage increases, the difficulty of interruption of the circuit increases approximately in proportion. The reason for this statement is quite obvious, for in the usual case final interruption takes place at a normal current zero. If the current and voltage are in phase, this time will coincide with that of the zero of the voltage wave, whereas if the current and voltage are 90 deg out of phase, the time of current zero will correspond to the peak of the voltage wave. Thus in interrupting a purely reactive short circuit, the breaker must establish, in a fraction of a millisecond, dielectric strength between its contacts equal approximately to the normal peak voltage to be established across them. This reasoning is confirmed by more or less isolated tests within the experience of most testing engineers.

Tests have been made by various investigators to determine the effect of power factor on arc duration.[3,4,5] Fig. 1 is taken from data obtained by Mr. F. Kesselring. It will be noted that the curves in this figure give an arc duration roughly approximating the second quadrant of an ellipse as predicted by the theory. This result is representative of those found by others.

These tests and theory indicate that there is a wide difference in the interruption between a purely reactive and a purely resistive short circuit. They indicate further, however, that in the region of a purely reactive short circuit, a considerable variation in phase angle may be allowed without greatly affecting the severity of the tests. Thus, while it is felt that the power factor conditions in factory testing plants are at least as severe as those to be encountered anywhere in the field, it is not felt that any slight discrepancy in this respect should be regarded as seriously influencing test results. In this connection, however, it should be borne in mind that there is a very appreciable effect upon recovery rate, depending on whether a short circuit limited partly by resistance and partly by reactance has the resistance and reactance in series or in parallel, the parallel case being very much easier. The above discussion applies to the series case.

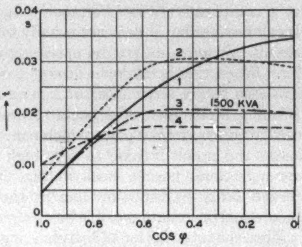

FIG. 1—RELATIONSHIP BETWEEN POWER FACTOR AND ARC LENGTH

1. Plain break
2. With large explosion chamber
3. With small explosion chamber
4. With six series breaks

Tests made at 1,000 kva, voltage not stated

From Kesselring[5]

In the case of leading currents, these conditions may not apply, and in the case of transmission line charging currents, the situation is quite different. Here at the time of the first current zero, the interruption is very easy. The reason for this is seen in Fig. 2. After interruption at instant *A*, the voltage of the transmission line remains constant as shown by the broken line; the

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[3] Wedmore, Whitney and Bruce, Jr., *Inst. Elec. Eng. Jl.*, 1929, Vol. 67, p. 557.

[4] G. Stern and J. Biermans, *E.T.Z.*, 1916, Vol. 37, p. 636.

[5] F. Kesselring, *E.T.Z.*, 1927, Vol. 48, p. 1278.

voltage of the source from which the transmission line has been disconnected is shown by the full line, and the difference between the two represents voltage across the circuit breaker. It will readily be noticed that this voltage does not rise abruptly to any appreciable value as in the case of a reactive short circuit nor does it even begin to rise with an appreciable rate as would be expected in the case of a resistive short circuit. The rate of rise initially is extremely small, and thus an initial interruption at least may be expected with a very small contact separation in almost any type of breaker.

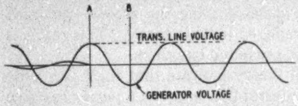

FIG. 2—INTERRUPTION OF TRANSMISSION LINE CHARGING CURRENT

One-half cycle after this initial interruption, however, at instant *B*, twice normal peak voltage appears across the circuit breaker contacts. In view of the short gap at which the initial interruption took place, this may be sufficient to break down the gap. This may take place at a comparatively low voltage in the case of an air-break breaker but it does not usually take place with oil circuit breakers on systems operating at less than 110 kv. When this breakdown does not occur, the circuit has been finally interrupted at a very short arc length. When a breakdown does occur, however, subsequent oscillations may take place which can build up voltage across the circuit breaker to very high values, five and one-half times normal peak voltage having been recorded on a transmission line in the field, and the theoretical maximum possible being almost unlimited.

Thus the interruption of line charging current may be the easiest duty the breaker has to perform on a low voltage system or may draw arc lengths approaching those obtained on short-circuit conditions on a high-voltage system. It must be remembered in this connection that the line of demarcation between what are here termed low voltage systems and high voltage systems depends entirely upon the breaker and may be well above any voltage in commercial use for some types of breaker. The oil-blast circuit breaker has been tested in this respect on the lines of the American Gas & Electric Company, a typical oscillogram being shown in Fig. 3. It may be noted that the arc lengths were very short and that voltages above twice normal were not encountered.

## RETARDATION

In most cases the alternator furnishing the power for factory interrupting capacity tests is driven by a motor just large enough to supply the no-load losses of the alternator. The question has therefore arisen as to the extent of generator retardation due to the additional losses occurring in generator, busses and reactors, and circuit breaker at the time of a circuit breaker test. Should this retardation be appreciable, the frequency and voltage would of course be reduced in the same ratio as the speed of the alternator. Measurements taken on the machine used by the company with which the authors are associated, however, indicate that this retardation is negligible. For instance, in an extreme case a three-phase short circuit might be left on for one-half second and then interrupted by a breaker dissipating a large amount of energy in the arc. A test has been made in which the duration of the short circuit was 28 cycles, but interruption was performed by a modern breaker dissipating a comparatively small amount of energy in the arc. The frequency was found to drop from 58 cycles per second to 56.8 cycles per second during the test. The rotational energy of the generator being 305,000 kw-sec at 60 cycles, the loss in energy represented by this retardation is approximately 12,000 kw-sec. Were a less effective breaker, dissipating more energy in the arc, used in such a test, the additional arc energy might in an extreme case run as high as 6,000 kw-sec for a three-phase breaker. This would increase the total energy dissipation to 18,000 kw-sec and reduce the generator frequency to 56.2 cycles, a total drop of 1.8 cycles or 3 per cent in frequency. Even this extreme case, therefore, does not give rise to sufficient change in the test conditions to warrant any correction, and it should be borne in mind that in a great majority of cases, the duration of short circuit is approximately one-fifth of that used in this example and the arc energy dissipated in the breaker not more than one-tenth that allowed here. Thus a drop of less than one-half of one per cent in frequency and voltage may be expected in most cases.

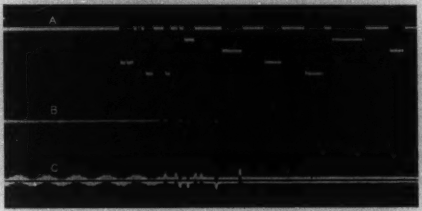

FIG. 3—OSCILLOGRAM SHOWING THE INTERRUPTION OF LINE CHARGING CURRENT

Curve *A*—Breaker travel
Curve *B*—Voltage across breaker
Curve *C*—Line current

## DECREMENT CURVES

The decrement of the short-circuit current affects the interrupting duty of the circuit breaker in two ways.

1. The arc current is slightly decreased from the time of contact separation to the time of interruption. Thus contact burning and oil deterioration are very slightly less than would be obtained with the same initial cur-

rent in the arc and no decrement. Obviously, the decay of both a-c and d-c components enters into this effect.

2. The recovery voltage is reduced, neglecting saturation, in the same ratio as the reduction in the a-c component of current from inception of short circuit to interruption. The effect of saturation is to decrease somewhat the amount of this reduction.

On both of these scores, therefore, the present A.I.E.E. specifications give the breaker credit for slightly more severe duty than it has actually withstood, for the reason that the current at the time of contact separation and the voltage before short circuit are used in the calculation of the severity of a test. Moreover, as the decrement of the a-c component in factory testing plants is usually steeper than is obtained in the field, these effects tend to make factory tests slightly less severe than field tests. With machines approximating standard design and breakers built to interrupt with a short arc duration and a short total duration of short circuit, however, both these effects are small enough so that the additional labor required in order to make a precise correction does not seem warranted, the maximum reduction in recovery voltage which might normally be expected in the testing plant of the company with which the authors are associated being about 25 per cent as against a reduction of 10 per cent to 15 per cent to be expected on an operating system. In the matter of current, the discrepancy probably is even less, not exceeding 5 per cent.

It is possible, however, to build machines which have a very rapid decrement of the a-c component, this component reaching a value of less than 50 per cent in 3 cycles. In these cases, it is felt that test results, unless made with special care to avoid this decrement, are subject to considerable question.

## Effect of Grounding the Short Circuit

The effect of grounding on a single-phase short circuit is primarily a matter of voltage distribution within the breaker. In the plain-break breaker, if one terminal is at ground potential, one break is likely to take the principal part of the recovery voltage, rendering the other break or breaks more or less ineffective, whereas if the two terminals are at equal but opposite potentials with respect to ground, approximately one-half the voltage will be applied to each of two breaks. With breakers employing special interrupting schemes, this effect is less likely to exist, for the arc lengths are in general shorter and this, in combination with the additional material used about the contacts, tends to increase the capacitance across the gap and thereby promote equal division of voltage.

The grounding of the neutral of a three-phase short circuit has several effects:

1. The magnitude of the recovery voltage to be established by the first pole to clear is reduced considerably.

2. One terminal of this pole, however, is at ground potential, whereas in the ungrounded case, one terminal is in general at plus $^2/_3$ of the total voltage with respect to ground while the other is at minus $^1/_3$. This tends to favor the ungrounded condition, as explained in the first paragraph under this heading.

3. In the ungrounded condition, the interruption of the first phase is the most difficult, whereas in the grounded condition the interruption of the last phase is likely to be so. Hence in the ungrounded condition there are three poles working simultaneously on the hardest task while in the grounded condition, the hardest task is left for one pole to accomplish. Furthermore, if there is any difference in the interrupting characteristics of the three poles, the one clearing last is likely to be the weakest.

The grounding of a three-phase short circuit, therefore, introduces tendencies in both directions, and the balance will be determined by the relative weight of the opposing factors in the particular case. In the case of the Philo tests,[6] the arc lengths for the two cases were on the whole, approximately equal.

The above discussion is predicated upon a system whose neutral is grounded. When the short circuit is ungrounded, it makes little difference whether or not the system neutral is grounded. A three-phase grounded short circuit on an ungrounded system, however, has the same properties as an ungrounded short circuit with the following minor exceptions, the first of which tends to increase and the second to decrease the severity of the test:

1. One terminal of the first phase to clear is at ground potential and the other at full potential above ground.

2. The recovery characteristic will have oscillations at two or more frequencies, at least one of which will be comparatively low, not more than two thirds of the total recovery voltage being associated with the high frequency oscillation.

In the laboratory of the company with which the authors are associated, tests normally are made with the short circuit grounded, but the system ungrounded.

## Relative Severity of Single-Phase and Three-Phase Tests

In both the factory and the field, it is often found convenient to deduce the performance of the breaker on three-phase short circuits from its performance on single-phase tests. In such cases, tests on a single pole may be made at leg voltage (58 per cent of line voltage) at 1.5 times leg voltage, or at full line voltage, depending partly on the application of the breaker and partly on the judgment of the testing engineer.

Tests at leg voltage are justified where the breaker is to be applied on a solidly grounded system and one so laid out that a three-phase ungrounded short circuit is impossible. Such arrangements are rare, however, and this type of test is very rarely sanctioned by the General Electric Company.

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[6] R. M. Spurck and H. E. Strang, *Circuit Breaker Field Tests*, A.I.E.E. Trans., Vol. 50, p. 513.

The choice of 1.5 times leg voltage arises from the fact that, in a location where the irregularities introduced by synchronous machinery have been smoothed out either by the predominance of other types of apparatus (current limiting reactors, transmission lines, cables, etc.) or by the presence of amortisseur windings, this voltage is encountered by the first phase to clear of a three-phase ungrounded short circuit. There are, however, additional factors, varying somewhat in importance from one application to another, which tend to affect the performance of the breaker. Thus the presence of synchronous machinery tends to increase the voltage which may be expected in the three-phase ungrounded condition, although this tendency may practically be eliminated by an amortisseur winding, or, to a lesser extent, by the iron of a solid steel round rotor.

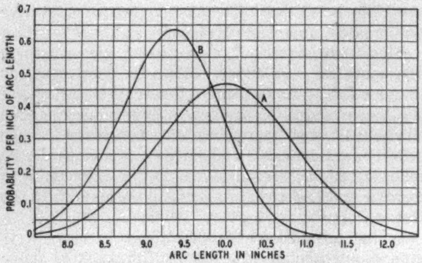

FIG. 4—CALCULATED PROBABLE DISTRIBUTION OF ARC LENGTHS FOR THE FIRST PHASE TO CLEAR OF A THREE-PHASE BREAKER (CURVE *B*) COMPARED WITH THE ASSUMED PROBABLE DISTRIBUTION FOR EACH POLE OPERATING INDEPENDENTLY UNDER SINGLE-PHASE CONDITIONS DUPLICATING THE THREE-PHASE CASE (CURVE *A*)

Each square represents a probability of 1 per cent

On the other hand, the fact that three poles are attempting to clear the circuit at different times and that success on the part of any one renders the task much easier for the other two, tends to increase the probability of clearing the circuit on three-phase tests in the early part of the region in which the circuit is interrupted in single-phase tests. Suppose for example that for a number of single-phase tests on a given breaker, the arc length varies as shown by curve *A*, of Fig. 4. Here the average arc length is 10 in. and the frequencies of arc lengths of 9 in. and 11 in. are both one-half that of a 10-in. arc length. On this basis the probability theory indicates that the first phase to clear of a three-phase short circuit in which all other conditions are equivalent to the single-phase case would be as given by curve *B* which has a most probable arc length of 9.4 in. and an average length of about 9¼ in. The mathematical development of curve *B* from curve *A* is shown in the Appendix. An additional consideration of slight importance lies in the fact that the decrement factor is lower in the case of three-phase short circuits than in the case of single-phase short circuits, resulting in a slightly lower recovery voltage for this case for the same short-circuit duration.

The use of full line voltage for single-phase tests has in general no theoretical basis but is sometimes used in both laboratory and field tests either because it is inconvenient to under-excite to the lower voltage or because more power is available at the higher voltage.

In the General Electric Company, tests are usually made at 1.5 times leg voltage, or 87 per cent of line voltage, and assurance is obtained that a liberal factor of safety is available even at this voltage, particularly when the breakers are likely to be applied where abnormally high recovery voltages may occur, as in the interruption of three-phase short circuits where power largely is supplied by waterwheel generators without amortisseur windings and without appreciable external reactance.

Stated in another way, in order to rate a three-phase breaker on the basis of tests on a single pole, the current interrupted by the breaker with a reasonable factor of safety is taken as the current which the breaker may be called upon to interrupt in three-phase application, and the test voltage is increased 15 per cent to give the line voltage of the system on which the breaker may be applied. The three-phase kilvoltamperes are thus $\sqrt{3} \times 1.15$ times, or twice the single-phase kilovoltamperes obtained in test, with a proper margin of safety on both current and voltage.

## EFFECT OF DISPLACEMENT

Displacement of the current wave, as is well known, has the effect of increasing the rms value of current. It also tends to render interruption easier by reducing somewhat the instantaneous value of recovery voltage. While the instantaneous value of recovery voltage may be reduced to zero in the case of a fully displaced wave, interruption is, as a rule, very difficult to accomplish before some decay has taken place in the d-c component of short-circuit current, and a small amount of decay in this component brings the recovery voltage comparatively close to that existing for a symmetrical current wave. For example, a wave with an 80 per cent d-c component has 60 per cent of normal recovery voltage and a wave with 60 per cent displacement has 80 per cent of normal recovery voltage.

## SHUNTS AND CURRENT TRANSFORMERS FOR CURRENT MEASUREMENT

From the point of view of accuracy, either shunts or current transformers may be used for current measurement, provided that they are properly designed and due precautions are taken with the secondary circuit. In the case of shunts, a standard design large enough from the heating standpoint and capable of withstanding the electromagnetic forces is satisfactory provided the drop lead is attached in the proper location and the spacing between conductors is sufficient so that no eddy currents are generated in one shunt by the flow of current in a neighboring conductor.

In the case of current transformers, the heating, electromagnetic stresses, and spacing must again be considered, and in addition consideration must be given to the section of iron to be sure that it is sufficient to record the d-c component without saturation. Saturation errors are much more serious in the case of a current transformer with secondary windings on one or two legs of a rectangular frame than in the case of a transformer with secondary windings uniformly distributed about a circular frame. Thus a special check must always be made of the secondary burden and the design of current transformers to be used for the measurement of short-circuit currents and in many cases especially designed current transformers may be required.

## Effect of Amortisseur Winding

An amortisseur winding increases the initial short-circuit current obtained from a generator but the increased current thus obtained is subject to a rapid decay. Thus if a short circuit is interrupted within 4 or 5 cycles after its initiation, the current may be increased some 10 per cent on account of the amortisseur winding. Beyond this point, however, the increase in current due to this cause is negligible. At the time of interruption, the recovery voltage will be decreased in about the same proportion as the initial short-circuit current is increased by the amortisseur winding unless the duration of short circuit is very short, in which case the normal voltage will be approached.

In the case of three-phase, ungrounded short circuits, the lack of an amortisseur winding may cause excessively high recovery voltage upon interruption of the first phase to clear. This renders the duty of the circuit breaker considerably more severe when interrupting a three-phase, ungrounded short circuit in a machine of this type.

## Arc Energy

A ballistic wattmeter which will indicate the instantaneous values of current and arc voltage is a part of the equipment of most interrupting test laboratories. Readings of arc energy are readily obtained and it is customary to take such readings for all interrupting tests.

It has not been found that arc energy has any consistent relation to the current interrupted. The readings are taken merely to give a general indication of the breaker performance and are used only in the analysis of results.

## Effect of the Form of the Recovery Characteristic

There are a number of tests on record in which the recovery characteristic of the system was subjected to some control while the circuit voltage and current were held constant:

On the 132-kv system of the American Gas & Electric Company at Philo, Ohio,[6] in the summer of 1930, the recovery characteristic was modified by changing the number of transmission lines connected to the bus, and recovery rates varying from 270 volts per microsecond to 2,400 volts per microsecond were obtained. Explosion chamber breakers were tested both with and without the oil-blast modification. In both cases the higher recovery rate gave about twice the arc length of the lower rate.

For the impulse breaker[7] it has been shown that for successful operation, a direct proportionality must be maintained between oil velocity at the contact tip and recovery rate. Data are available indicating that the same thing is true of other oil-blast breakers, as would naturally be expected.

Tests reported by Doctor Kopeliowitch[8] showed a two to one change in arc length resulting from a change in the frequency of the recovery characteristic from 350 cycles per second to 1,500 cycles per second. The change in recovery rate would be proportional to the change in frequency. This presumably refers to a high voltage multi-break breaker. Doctor Kopeliowitch also states that the interrupting capacity of a compressed air circuit breaker could be increased 2.6 times by a reduction of the recovery characteristic frequency from 18,600 cycles to 7,200 cycles.

Mr. C. L. Denault[9] records a large change in the arc length of a small plain-break breaker produced by manipulation of the recovery characteristic.

In the great majority of cases, the factor determining the recovery characteristic[10,11] is the capacitance present in the system and its location with respect to the system reactance and the circuit breaker. A large capacitance to ground, located between the breaker and the principal reactance of the system, tends to delay the appearance of voltage across the breaker and give rise to a mild recovery characteristic, whereas the lack of such capacitance causes a steep and therefore severe recovery characteristic. For this reason a breaker used to isolate a fault from a bus to which are connected a large number of transmission lines or cables, if there is no appreciable reactance either between the fault and the breaker or between the breaker and the bus, will have a mild recovery characteristic. If, however, a current limiting reactor or a transformer is inserted in the circuit close to the breaker on either side, the recovery characteristic may become very severe. A special instance of the transformer case is that in which the breaker is used to protect a mercury arc rectifier installation. The duty of such a breaker has long been known to be severe, but it is only recently that the explanation has been found in the recovery characteristic.

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[7] D. C. Prince and E. J. Poitras, "Oil-Blast Breaker Theory Proved Experimentally," *Electrical World*, February 28, 1931.

[8] J. Kopeliowitch, "Influence of the Form of the Voltage on Breaking the Circuit on Operation of Circuit Breakers," *Bulletin of Swiss Association of Electricians*, June 26, 1931.

[9] "Circuit Breaker Duty Affected by Speed," *Electrical World*, Nov. 15, 1930, Vol. 96, p. 913.

[10] R. H. Park and W. F. Skeats, *Circuit Breaker Recovery Voltages*, Trans. A.I.E.E., Vol. 50, p. 204.

[11] W. F. Skeats, "Circuit Breaker Duty Affected by Characteristics of Circuits," *Electrical World*, June 27, 1931.

The feeling has been prevalent in the past that the recovery characteristics obtained in the field always were less severe than those normally obtained in factory testing plants. While this situation undoubtedly prevails in the great majority of cases, a few exceptional instances have arisen of late in which the field recovery rate was several times the factory test rate on standard connections. In such cases it is possible to set up a special arrangement in the factory whose recovery rate will equal that to be obtained in the field. Such a setup is shown in Fig. 5. Here the current limiting reactor is placed as close as possible to the circuit breaker and the two are connected by a very short jumper. The capacitance between the two is thus maintained at a minimum.

## SPECIAL CONSIDERATIONS IN THE CASE OF VERY HIGH SPEED BREAKERS

In the case of breakers which clear uniformly on the first normal current zero after separation of the contacts, the duty imposed on the breaker may vary over wide limits, depending on the time in the current cycle when the contacts are separated. Thus if separation occurs a very short time before current zero, the current in the arc may not exceed a few thousand amperes although the rms value of short-circuit current may have been as high as fifty thousand amperes. In such a case the circuit often is opened with no perceptible evidence of short circuit on the part of the breaker.

If, however, the contacts separate at the beginning of a current loop, arcing will continue throughout the remainder of the loop, and a comparatively large amount of gas will be generated. In comparison with the other case, a rather large disturbance may be noted when this occurs, although with this type of breaker, the distress is not severe in any case.

In the case of a displaced wave, the range of variation of breaker duty is likely to be considerably greater than in the case of a symmetrical wave, both because the rate of change of current is less in the neighborhood of current zero, and because the maximum possible duration of current is greater.

## EXTRAPOLATION

The method of extrapolation of results to obtain rated capacities beyond the limits of the testing equipment is dependent on the type of breaker under consideration. The extrapolation of results of tests on plain-break breakers is particularly difficult because of the erratic performance of the breaker and the extent to which its arc duration increases with increase in voltage. When necessary to extrapolate for plain break breakers, the most satisfactory method is to test at rated voltage and varying current up to the limit of testing facilities. From these tests a kva pressure curve is plotted which, if enough tests have been made and the curve has a definite trend, may be extended a reasonable distance within the known pressure limits of the breaker structure. It is not considered even reasonably dependable to extrapolate from tests made at rated current, but at a reduced voltage, because there is little or no assurance that the arc length at the reduced voltage will approximate the arc length at the same current at normal voltage. Also, the susceptibility of the plain-break breaker to variation in recovery voltage may give very misleading results from such tests.

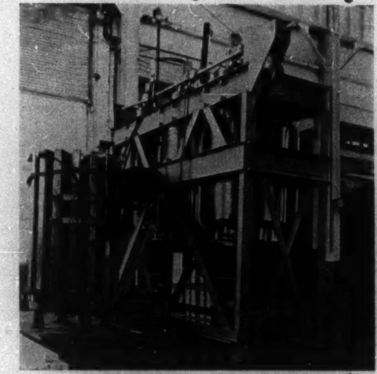

FIG. 5—SPECIAL LABORATORY ARRANGEMENT FOR OBTAINING UNUSUALLY HIGH RECOVERY VOLTAGE RATES

Most oil-blast breakers have the property that the arc length is nearly constant over a wide range of voltage. Therefore, the stress on the breaker at any current is about the same regardless of the voltage. The procedure in making extrapolation tests on oil-blast breakers is to test at rated voltage at currents as high as are available. These tests will establish the arcing characteristics and check the design for consistent arc length. The tests then are carried on at a lower voltage where more current can be produced. As long as arc lengths even at the lower voltage are approximately the same length as those at the higher voltage, it appears reasonable to base the rating of oil-blast breakers on the product of volts and amperes obtained from separate series of tests.

## SUMMARY

Short-circuit testing laboratories not only have been used as proving grounds for checking oil circuit breaker ratings but have been used also for research on the fundamentals of and the development of new methods for circuit interruption. From the research work made possible by the availability of such laboratories, the effects of many variables entering into breaker performance have been determined and several new types of breakers have been developed. Also, such a complete analysis has been made of the differences between laboratory testing and field service that their relationship can be judged accurately.

Though the short-circuit currents available in even the largest laboratories do not permit the testing of the larger capacity breakers at rated interrupting current and voltage, nevertheless so much knowledge has been obtained on oil circuit breaker performance that tests on modern breakers at the laboratory can be extrapolated to the larger capacities with confidence. This is borne out by field tests which have checked laboratory tests and by the fact that breakers tested in the laboratory have given the required service in regular operation.

## Appendix

*Calculation of the probable distribution of arc lengths for the first phase to clear of a three-phase breaker from an assumed distribution in accordance with the standard probability curve for each pole of the breaker operating independently, single-phase, under current, voltage, and recovery rate conditions duplicating those of the three-phase case.*

The equation corresponding to the example chosen is

$$y_1 = 0.470\, e^{-\left(\frac{x-10}{1.2}\right)^2} \tag{1}$$

where $y_1$ is the probability of occurrence, per inch, of an arc length of $x$ inches. Thus the probability of occurrence of an arc length within 0.01 in. greater or less than $x$ is $2 \cdot 0.01 \cdot y$.

These constants give a most probable arc length of 10 in. with the probability of arc lengths of 9 in. and 11 in. each half that of 10 in. The curves are plotted in Fig. 4 in such a way that one square of the cross-section paper represents a probability of 0.01.

The probability, $z_1$, of occurrence of an arc length less than a value $x$ for the single-phase case is given by the equation

$$z_1 = \int_{-\infty}^{x} y_1 dx \tag{2}$$

The probability of occurrence of a longer arc length in this case is $1 - z_1$, and the probability that all three poles in a three-phase test will have arc lengths greater than $x$ is $(1 - z_1)^3$. The probability $z_3$, that the first phase to clear of a three-phase test will have an arc length less than $x$ therefore is

$$z_3 = 1 - (1 - z_1)^3 = 3z_1 - 3z_1^2 + z_1^3 \tag{3}$$

and the equation of the corresponding probability curve is

$$y_3 = \frac{dz_3}{dx} = 3\frac{dz_1}{dx} - 6z_1\frac{dz_1}{dx} + 3z_1^2\frac{dz_1}{dx} \tag{4}$$

But from equation (2), $\frac{dz_1}{dx} = y_1$. Hence,

$$y_3 = 3y_1(1 - z_1)^2$$

$$= 1.41\, e^{-\left(\frac{x-10}{1.2}\right)^2}\left[1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx\right]^2 \tag{5}$$

The bracket of equation (5) may be evaluated as follows:

$$1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx$$

$$= 1 - \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)} d\left(\frac{x-10}{1.2}\right) \tag{6}$$

But

$$\frac{1}{\sqrt{\pi}}\int_{-\infty}^{0} e^{-\left(\frac{x-10}{1.2}\right)^2} d\left(\frac{x-10}{1.2}\right) = \frac{1}{2}$$

(This is one-half of the standard probability integral for infinity.)

Hence,

$$1 - 0.470\int_{-\infty}^{x} e^{-\left(\frac{x-10}{1.2}\right)^2} dx$$

$$= \frac{1}{2}\left[1 - \frac{2}{\sqrt{\pi}}\int_{0}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)} d\left(\frac{x-10}{1.2}\right)\right] \tag{7}$$

But

$$\frac{2}{\sqrt{\pi}}\int_{0}^{\frac{x-10}{1.2}} e^{-\left(\frac{x-10}{1.2}\right)^2} d\left(\frac{x-10}{1.2}\right)$$

is the probability integral for $\frac{x-10}{1.2}$, and its values are given in standard tables. Using these tables, therefore, and performing the other operations indicated in equations (5) and (7), the value of $y_3$ can be determined for any value of $x$. Curve *B* of Fig. 4 was plotted in this way.

It is obvious from inspection of curve *B* that the average arc length to be expected from it is somewhat less than 9.40 inches. A precise calculation gives 9.282 inches.

It will readily be seen that the decrease in the average arc length from the single-phase case to the three-phase

**case exists regardless of the shape of the probable distribution curve applying, except for the hypothetical case in which there is no variation whatsoever in the arc length of the single-phase case, when the arc lengths for the two cases are the same. The amount of the decrease depends upon the extent of variation of the arc lengths for the single-phase case.**

## Discussion

**Philip Sporn:** Only as recently as 20 years ago it was quite common, when selecting oil circuit breakers, for the designing or operating engineer to give a system one-line diagram to the manufacturer, and from that diagram the breakers were selected or recommended on the basis of so-called system reactance and type of tripping employed. The art of breaker selection was considered at that time a highly esoteric one. The historic paper of Hewlett, Mahoney and Burnham[1] changed all that, and utility engineers began to realize that the short-circuit capacity that a breaker might be expected to rupture in case of a fault could actually be calculated for various system arrangements and that it could be calculated with a reasonable degree of accuracy. This in turn made possible the assignment of definite short-circuit capacities or ratings in amperes or kilovolt-amperes to oil circuit breakers and left it to the electric system designer or operator to select a breaker that would give him the best engineering economic balance for both his immediate and future requirements.

However, the art of designing oil circuit breakers continued on a rather unsound basis until the development of testing laboratories among the manufacturers. Some 10 years ago it was definitely recognized, however, that the amount of information that could be obtained in the then existing laboratories was rather limited and that for a full determination of the suitability of breakers of any particular design for a given system, field tests would be necessary. In 1925 and 1926 an extensive series of such tests was carried out on one of the 132-kv systems with which the writer is associated, and it is interesting to recall the fact that a great many operators and operating engineers criticized this action as subjecting the power system to undue hazards. Nevertheless, and because of the fact that the results obtained in these tests were so productive of advancing breaker design and of giving the operators the necessary assurance that equipment installed for system protection actually was capable of performing satisfactorily at time of system disturbance, breakers continued to be tested in the field. This did not arrest the continued development of more complete manufacturers' laboratories, but with this development the idea became prevalent among a considerable number of operating and designing engineers that all breakers were being tested up to their rating in manufacturers' laboratories, and that it was possible to purchase breakers for almost all ratings that had been fully tried out in the laboratory; there was no question, therefore, that breakers so purchased could perform up to and within their rating entirely satisfactorily in the field.

Such, of course, was not the case. The Association of Edison Illuminating Companies, recognizing this, appointed a committee about a year ago to investigate and report on the general question of oil circuit breaker testing, more particularly oil circuit breaker testing in the laboratory. In the discussions with manufacturers' engineers and designers this committee brought forth and gathered a great deal of information along the lines presented by the authors of the paper. It is obvious, however, that this paper presents the authors' aspect of the very important problem of rating and selection of oil circuit breakers; that is, it gives a fairly complete idea of the testing procedure and interpretation of the manufacturing group with which the authors are associated. Before the entire problem is brought to the proper state of knowledge it will be necessary to get similar data from other manufacturing groups and if possible bring some of the conflicting ideas into harmony. It is hoped that the committee report referred to above will be able to accomplish this, but obviously any further presentation of data on the part of the engineers of other manufacturing companies will help this matter along materially.

The authors, while giving a very excellent presentation of their end of this very important subject, show a tendency to fall into a very common error committed possibly from time immemorial in connection with all engineering developments and more particularly in connection with oil circuit breakers, and that is the assumption that the present is finally the time when all knowledge necessary in connection with the design of oil circuit breakers is available. Thus, they say that although "the short-circuit currents available in even the largest laboratories do not permit the testing of the larger capacity breakers at rated interrupted voltage, nevertheless so much knowledge has been obtained on oil circuit breaker performance that tests on modern breakers in the laboratory can be extrapolated to the larger capacities with confidence." I note they do not say "with safety." It is highly questionable whether that can be done; but there does not seem to be any doubt that proper testing in the laboratory can contribute greatly toward the development of a breaker so that it has a reasonable chance of satisfying the performance specification. It is questionable, however, whether for some time to come any substitute will be found for testing a breaker under actual field conditions if actual knowledge of the ability of the breaker to perform satisfactorily is desirable.

Several other aspects of oil circuit breaker testing are commented upon at this particular time:

It would appear that additional field testing is highly desirable in order to determine recovery limits and rate of recovery voltage rise that may be expected on different types of electric power systems, and laboratory and field tests to determine the ability of various types of breakers to perform under these conditions of differing rates of recovery voltage rise. Further, additional information, both theoretical and laboratory is necessary and desirable to determine the effect on rate of rise of recovery voltage of different types of breakers.

In a discussion of the series of papers on the Philo 1930 oil circuit breaker tests,[2] the writer suggested that the standard A.I.E.E. duty cycle on oil circuit breaker capacity was in line for revision to take into account newer developments of the oil circuit breaker art and changes in operating practice. Since then a joint E.E.I.—A.E.I.C. committee has been at work on this problem together with the manufacturers' engineers, but the development of a cycle that would fit modern operating conditions is being greatly handicapped owing to the lack of sufficient information, particularly test information as to the effect of proposed duty cycles upon present designs of breakers and more particularly upon newer designs in prospect. It would seem that some laboratory work on this particular problem is highly desirable, and perhaps indispensable, before a new duty cycle can actually be formulated properly; there appears to be no doubt that a new duty cycle is very much needed at the present time.

**H. P. St. Clair:** As a member of the Association of Edison Illuminating Companies on circuit breaker testing referred to by Mr. Philip Sporn and having spent a considerable amount of time during the past year in the study of oil circuit breaker testing, particularly as regards the testing that is carried out in the laboratories of the various manufacturers, the writer was particularly interested in Messrs. Spurck and Skeats's paper. This paper is an indication that the extensive work being carried on by this committee will have a twofold value: first, from the standpoint of the committee report itself, which report it is hoped will be of considerable interest and value; and second, from the standpoint of stimulating the preparation and presentation of such papers as this one on the subject of circuit breaker testing. It is hoped that other papers along this line may be forthcoming.

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[1] See TRANSACTIONS A.I.E.E., vol. 37, part I, pp. 123-165.

[2] TRANSACTIONS A.I.E.E., vol. 50, p. 518.

**W. D. Ketchum:** As a member of a working subcommittee of the Association of the Edison Illuminating Companies the writer has for about a year been devoting a substantial portion of time to an investigation of the oil circuit breaker testing facilities and technique of the various manufacturers. The present paper is, therefore, of very keen interest.

Undoubtedly this paper will contribute toward a better understanding of circuit-breaker testing problems than most members of the industry have had heretofore. There is one point, however, which seems to deserve more detailed treatment than the paper gives it: the influence of the decrement of the short-circuit current upon breaker performance on OCO tests. The authors give the impression that it is only on poorly-designed breakers that the OCO test is much more severe than the CO test. They do not mention the effect of decrement upon the OCO test as distinct from the CO.

It may be true that for a single OCO test where the decreemnt is slight the OCO test would not be much more severe than the CO. However, when a multi-shot cycle is made, with a substantial decrement, the effect upon the breaker may be much more severe than in the case of the same number of CO shots. This is particularly true for heavy current values such as exist when the test is made at lower than rated voltage. In fact, under these conditions the decrement actually can become a limiting factor on breaker performance, as the current to be closed may exceed the instantaneous current-carrying capacity of the breaker. For example, a 175,000-kva, 15-kv breaker might be tested at 4 kv. If tested in a laboratory having only a slight decrement it would be called upon to close and open about 25,000 amperes. If tested with a more substantial decrement, however, it might have to close 50,000 amperes and open 25,000. If the short-time current rating of the breaker is only 40,000 amperes, the decrement in this case actually has the effect of derating the breaker.

Even if the rating of the breaker is reduced for a multi-shot cycle, the cumulative effect of contact burning still may be sufficient to cause distress or failure. In my own experience, on tests of this type with a steep decrement, contacts have welded together in closing and been destroyed; even though the breaker showed no distress in interrupting. The same breaker tested where the decrement was less severe might show no distress at all. It should be pointed out here that on account of the inherent time required for breaker operation, plus whatever time may be introduced by the relay settings, the serious consequences associated with substantial amounts of decrement that have been discussed above can occur when the decrement conditions are much less extreme than the case pointed out by the authors where the decay amounted to 50 per cent in three cycles.

Other factors besides contact design are involved in this problem. If the breaker does not latch on the closing stroke it starts opening with less than normal stored energy in the opening springs and its contacts part with less than normal velocity. These conditions penalize the breaker. In order, therefore, to be assured of satisfactory field operation, OCO tests must be made under decrement conditions comparable with those in the field. This means that tests in one laboratory are not necessarily comparable with those in another having different decrement conditions and that neither is necessarily representative of field conditions.

Since under the new derating schedule now being considered by the industry, the derating factors for multi-shot cycles largely are determined by contact deterioration, it follows that in order for these factors to have any meaning, constant decrement conditions must be specified.

All of the foregoing discussion leads to the conclusion that since the results of tests made under different decrement conditions are not directly comparable, uniform decrement conditions should be maintained whenever possible in testing. Furthermore, the uniform decrement decided upon for testing should approximately represent the most substantial decrement which will be encountered in the field. Where it is impossible to modify the existing facilities or the present technique of testing in order to achieve the desired decrement rate, the results should be adjusted to compensate for the discrepancy between the actual and the desired decrement curves. In order to determine the extent of the adjustment which would be needed, it would probably be necessary to test the same breaker in laboratories having different decrement conditions but with the same interrupted current. In this manner the extent of the influence of decrement could be determined. Until some recognition is given this situation, the results of factory tests cannot be compared directly nor can they be considered as a reliable index of the performance of the breaker in the field.

**J. K. Ostrander:** Predicting the interrupting ability of a breaker by processes of extrapolation from test data, as briefly described in the paper, apparently is reliable if the breaker operates in a circuit with a reasonably low rate of rise of recovery voltage, but it is not obvious that accurate results can be obtained by extrapolation from test data for high rates of rise of recovery voltage.

A high rate of rise undoubtedly will have a tendency to increase the arcing time. Therefore, if the breaker is tested with a high current and a low rate of rise, or a low current and a high rate of rise, it is not apparent that the operating ability at both high current and high rate of rise can be determined by the process of extrapolation referred to in the paper, unless it is proved that the curve plotted with arcing time against current is not changed by a change in recovery voltage.

Many large power stations operate at voltages up to 13,200 volts, with feeders and generators connected directly to the busses without transformers, the breakers being protected by current limiting reactors. In such circuits, a reactor may be quite close to the breaker and the electrostatic capacity of the circuit between the reactor and the breaker may be less than 1,000 micromicrofarads. If a short circuit occurs near the outer terminal of the reactor in such a case, the frequency of oscillation at the time of circuit interruption may be over 100,000 cycles per second and this may produce a rate of rise of recovery voltage in excess of 5,000 volts per microsecond.

For such an installation, it is desirable that the interrupting ability of the breaker be proved by some reliable process of extrapolation if it can not be tested at the factory at rated interrupting capacity and at the same rate of rise of recovery voltage as might be expected in service.

**W. F. Sims:** The rupturing performance of circuit breakers can only be established by tests made under a variety of conditions which can be controlled. This was demonstrated in the field tests made at the Crawford Avenue Station of the Commonwealth Edison Company during the years 1928 to 1930. While some information can better be obtained in field tests, in general, factory tests are preferable because of the better control of conditions. Also, laboratory equipment is required to check the many elements of circuit breaker performance, and this is not always available in the operating companies.

It also is difficult to find a suitable and safe testing site on an operating system, and testing on commercial circuits is a hazard to apparatus, which may affect continuous service to customers. Further, a trained staff of testing engineers, embued with the testing spirit, is available at the factory, whereas the engineers of an operating company are not temperamentally adjusted to experimental testing, and as they are trained to keep apparatus in service and not to find its defects, they are more easily discouraged by failures.

It is essential to test the closing ability of breakers on short circuits in order to determine the presence of unexpected magnetic, frictional, and hydraulic forces. CO tests greatly increase the available current capacity of the testing equipment, and are probably of more importance in field testing than in the factory. Short circuits of 5 to 8 cycles on a 60-cycle system may be applied to a commercial system with little disturbance if they are not too closely coupled with the system load. Short circuits of greater duration are likely to have an undesirable effect on the system. As few circuit breakers will close and open in 8 cycles, the CO tests increase the short circuit that may be applied without injurious system effects.

The statement that cable circuits are favorable to the rupturing performance of circuit breakers is confirmed by experience on the 12-kv, 60-cycle circuits of the Commonwealth Edison Company, where unfavorable performance is very rare. On the same circuits the extensive use of reactors does not seem to have an objectionable effect, possibly because the reactors used are relatively small and are compensated for by the over-capacity of the cables.

This paper definitely leaves the impression that the statements made regarding the elements affecting breaker performance are not those of opinion only but that they have been fully confirmed by test. Such items as the effects of grounded or ungrounded circuits, single- or 3-phase operation, d-c components, wave forms, and recovery voltage have long been subjects of controversy. This presentation is a valuable and timely one and the authors deserve the thanks of engineers interested in this subject for the definite contribution to our knowledge of these factors.

**J. Slepian:** This paper gives an excellent review of the many factors which must be considered in the testing of circuit breakers in high power laboratories. It will be very valuable to research and development engineers who make such tests and to operating engineers who must conclude from such tests how breakers will perform in their systems. Particularly interesting is the section "Effect of the Form of the Recovery Characteristic" because from the study of such effect, much may be learned about what goes on in the short interval of time embracing a current zero when the arc space changes from conductor to insulator and accomplishes the whole purpose of the breaker, namely the actual opening of the circuit.

Except for the third paragraph in this section, in no case is there found anything like a proportionality between the "recovery rate" and the rate of recovery of dielectric strength of the arc space, which, in most breakers at least, should be expected to be nearly proportional to the arc length. By "recovery rate" is meant here, as also in the paper, the slope of the volt-time transient of the circuit calculated merely on the hypothesis that the arc space suddenly becomes insulating at current zero. It does not correspond to the actually occurring transient which as shown in the paper by Van Sickle and Berkey (see page 850) begins well before the current zero, and is considerably modified by the conductivity of the arc space.

Thus, in the Philo tests mentioned in the paper a multiplication of the recovery speed by 8.9 required only a two-fold increase of arc length, and in the oil breaker tests quoted from Kopeliowitch, an increase in the natural period of the circuit of 4.3 times again required only a doubled arc length. Only for the oil-blast breaker in the third paragraph of the section is it stated that there is a proportionality between the "oil velocity" and the "recovery rate."

The experimental basis for this conclusion and the theory advanced for the oil blast breaker were criticized by the writer and others (Discussion, Trans. A.I.E.E., March 1932, p. 191) and no reply was given. This conclusion again is contradicted by the quoted Philo tests, for if the arc is extinguished by the formation of an oil barrier at a definite speed, there should have been no change in the arc length, and it is very difficult to see why doubling the arc length in an oil blast breaker operating in its reputed way should make it handle a nine-fold greater "recovery rate."

The results mentioned in this paper are consistent with the thought that the arc space possesses considerable dielectric strength even before the current zero, an idea which is supported by the cathode-ray oscillograph study of oil breakers by Van Sickle and Berkey, and the special test described in the writer's paper in *Elektrotechnik und Maschinenbau,* April 1933. This means that we must, to some extent, give up the simple picture now generally held and which was perhaps first proposed in the paper, Trans. A.I.E.E., v. 47, 1928, p. 1398, according to which the extinction of the arc depends on a kind of race between the "recovery rate" calculable from the circuit constants alone, and the rate of recovery of dielectric strength of the arc space, determined from the nature of the arc alone, this race starting precisely at current zero. That this picture needs to be modified is important because there is a disposition on the part of some engineers leaning too heavily on the simple theory to feel that we may now attach a "recovery rate" rating to circuit interrupters.

**R. M. Spurck and W. F. Skeats:** Mr. Philip Sporn mentions the desirability of field tests to determine the recovery rates likely to be met in practice. Properly conducted field tests from which recovery rates are measured with the cathode ray oscillograph are useful in determining or checking expected recovery voltage rates. As such tests are relatively expensive, a study has been made of the possibility of calculating the recovery rates of various systems from the system and apparatus constants which can be more readily obtained. The company with which the authors are associated is assembling such data and hopes that some checks of its findings will be obtained from field tests.

The authors did not intentionally create the impression that all the knowledge necessary for switchgear design is available at the present time. The oil circuit breaker testing plant of the company with which the authors are associated is continually in use in the development of new conceptions of circuit breaker performance and obtaining new information with regard to circuit breakers, and all data obtained are examined critically to determine whether they indicate that any previous assumptions with regard to circuit breaker testing or performance must be modified or discarded.

We concur with the hope expressed by Mr. H. P. St. Clair and implied by other discussors that similar papers be presented by others who have had experience in oil circuit breaker testing.

Mr. W. D. Ketchum has raised the point of the increase in closing-in current required by a steep decrement curve on an *OCO* test when the breaker is interrupting its rated current. In this connection it should be borne in mind that even in the field, in the ideal case where there is no decrement of the a-c component, it may be expected that the breaker will have to close-in on a current 73 per cent greater than it interrupts, due to the presence of a d-c component at the time of closing-in and its absence upon interruption. With the testing generators used in this country, and reasonably fast tripping of the breakers, the ratio should not exceed two to one. Thus the difference between field and laboratory conditions is not so great as would appear at first sight.

We feel that by the use of the testing facilities that are available, the conditions discussed by Mr. W. D. Ketchum can be approximated and in actual testing work, tests are made to determine the adequacy of breakers under those general conditions. Particular attention is given to the design and test of breakers to insure that they have sufficient opening tendency for proper interruption even though they may be required to open before being entirely closed.

Mr. J. K. Ostrander suggests that breakers should be tested simultaneously at the full recovery rate at which they are to be applied and at full rated current. In exceptional cases, it is just as difficult to do this as to test at full voltage and full rated current. It is the opinion of the authors, however, that the behavior of the breaker under conditions of full recovery rate and full rated current may be determined by tests covering the two conditions separately, provided that the arc length is the same in both cases.

A special test circuit has been set up to approximate the high recovery rate mentioned by Mr. Ostrander and breakers tested under those conditions at the factory. Subsequent field tests under high recovery rate conditions indicated that the performance of the breaker during the factory tests was consistent with the performance during the field tests.

Doctor Slepian has raised a question somewhat irrelevant as far as this paper is concerned. He asks why no proportionality is found between voltage recovery rate and arc length. We see no reason why there should be any. The space between the contacts is not homogeneous, but is filled partly by oil of high dielectric strength and partly by gas of low dielectric strength. The rate at which the portion of high dielectric strength is built up is the important factor and does not bear any necessary relation to the contact separation beyond some minimum distance. This point was discussed at length by Mr. D. C. Prince in the closing discussions of the papers, *The Oil-Blast Circuit Breaker*, D. C. Prince and W. F. Skeats, presented January, 1931,* and *The Theory of the Oil-Blast Circuit Breaker*, D. C. Prince, presented January, 1932.†

The desirability of the assignment of a recovery rate rating to oil circuit breakers is not, as Doctor Slepian suggests, dependent on a modification of the conception that during interruption there is a race between the growing dielectric strength between the contacts and the voltage building up across the contacts. In our opinion, the reason for recognizing recovery voltage in the interrupting rating of breakers is that the performance of the breaker is influenced by the recovery rate determined purely as a system characteristic. That there is a pronounced influence has been shown many times in the literature. It therefore behooves both manufacturer and operator to satisfy themselves that a breaker purchased for a given location is capable of handling the recovery rate to be experienced at that location, just as it behooves them to satisfy themselves similarly with regard to voltage and current. The actual assignment of ratings must wait, however, until more information is available regarding both system requirements and breaker performance.

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*A.I.E.E. Trans., June 1931, p. 528.

†A.I.E.E. Trans., March 1932, p. 197.

# A Compression Type Low Voltage Air Circuit Breaker

BY D. C. PRINCE[1]
Fellow, A.I.E.E.

FOR a great many years the use of fuses or fused switches for low-voltage low-current distribution circuits and for various other applications has been quite common. These have done their work quietly with no loud poppings and spurts of flame and have proved so reliable that were it not for the expense and annoyance of locating the blown fuse and replacing it one or more times before the trouble is cleared up, it would not be necessary now to offer an alternative method of protection.

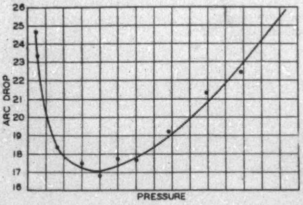

FIG. 1—VARIATION IN ARC DROP AS A FUNCTION OF PRESSURE

In developing a replacement unit, it seemed desirable as far as possible to retain the good points of the fuse, adding to its properties of silence and complete inclosure, the convenience of a trip indication and convenient reclosure to restore service. If silent operation were to be obtained, the magnetic blowout with its pop and spurt of flame seemed to be ruled out. The fuse did not pop and had no openings for emission of flame. Without the space for drawing out the arc and with expulsion eliminated, it was necessary to develop a new theory which can explain the operation of the fuse and then apply that theory to a circuit breaker.

The potential drop in an arc varies with the pressure substantially as shown in Fig. 1. For very low pressures, it is quite high. As the pressure is increased, the voltage drop comes to a minimum and then rises again. The pressure for minimum arc drop is likely to be of the order of 0.1 mm. The form of the curve is explained by ionization considerations. The current flow is carried largely by electrons. These make collisions with the gas molecules and in a certain fraction of cases, strike off other electrons, leaving the previously neutral molecule charged as a positive ion. These positive ions neutralize the negative electric field of the electrons, permitting the latter to travel rapidly through the space without doing any work. In the absence of any gas or vapor molecules in the space, the accumulation of electrons produces a negative space charge that can be overcome only by high voltage on the positive electrode.

After an ion is formed it continues to move to and fro striking other molecules, electrons or the walls of the vessel. At low pressure, many ions strike the walls where they are held stationary until neutralized by an electron, when the energy is lost to the wall. This loss of ions must be made up by increasing the average velocity of the electrons so that more collisions will produce ionization. This requires higher voltage drop. As the pressure rises, more and more ions will be turned back by collision with neutral molecules, before reaching the wall. The loss to the wall will decrease and hence the voltage drop due to this loss will decrease. A moving ion is a much more difficult target for an electron to hit; collisions with ions will then be less frequent. The radiation resulting from the collision may not all be lost so that the average loss per collision becomes less. Because of these two effects, a reduction in loss to the wall is not entirely offset by increased losses elsewhere, and at low pressure a net reduction occurs with increase in pressure.

When ion and electron collide away from a wall, energy is radiated which may ionize a second molecule in the arc stream or escape from the arc stream and be lost as far as assisting electron passage is concerned. As pressure is increased, these collisions become more and more frequent so that more and more energy is lost by radiation and absorption. The paths of the electrons are also shortened by the increase in pressure, so that a greater potential drop per unit of distance is required to get the necessary number up to ionizing velocity. The voltage required to make up losses thus rises rapidly with pressure and at a pressure of several atmospheres,

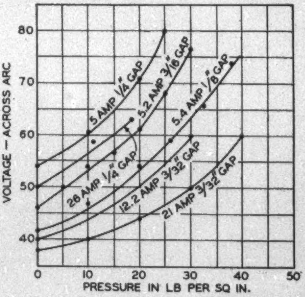

FIG. 2—ARC DROP OF A CARBON ARC IN AIR UNDER PRESSURE

more voltage may be required to maintain an arc than the attached system can provide. In that case, the arc goes out.

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[1] General Electric Company, Philadelphia, Pa.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933*

The total arc drop will be due to the sum of two components made up of losses decreasing with increase in pressure and the other made up of losses increasing with increase in pressure and will be of the form of Fig. 1 which was made up from data taken in connection with mercury arc investigations. For low pressures the former predominates and the total voltage falls with increasing pressures. For higher pressures the latter predominates and the total voltage drop increases with increasing pressures. Interruption of circuits by a pressure device involves the phenomena accompanying increase in pressure. Fig. 2 shows the drop in a carbon arc in air. The pronounced increase in arc drop with increase in pressure is apparent. If a constant voltage is applied to the arc, the length of the gap over which an arc can be sustained decreases with the increase of pressure on the arc. Fig. 3 shows the length of arc between carbon electrodes that can be maintained by a non-inductive circuit supplied from 125 volts direct current.

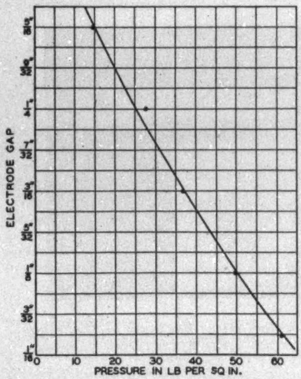

Fig. 3—Arc Extinction Between Carbon Electrodes in Air Under Pressure

Arc drop is not dependent on pressure only. It is well known that the drop of voltage in an arc goes down with increase in current so that some series impedance is necessary to maintain constant current. At constant pressure, the cross sectional area of an arc probably is proportional to the current or nearly so. The losses are concentrated along the arc boundaries so that they are proportional approximately to the surface area of arc stream or to the square root of the current and cross sectional area. The losses in watts are of course equal to the product of instantaneous current and arc drop. The arc drop therefore is approximately proportionate to the inverse square root of current. This reasoning is not exact and rigid but is correct qualitatively and serves to show the relationship between the arc characteristics as influenced by pressure and current. On account of the inverse nature of the arc drop at constant pressure, the current when increasing tends to increase indefinitely until limited by some other part of the circuit, and when falling, the arc drop rises promoting a further fall in current until the arc goes out. An arc at constant pressure is not a suitable circuit interrupting agency but if the condition of falling current can be established by lengthening, by magnetic blowout, or otherwise, or by increasing pressure so as to produce with increased current an increased arc drop, the current then will begin to decrease and eventually will cease flowing.

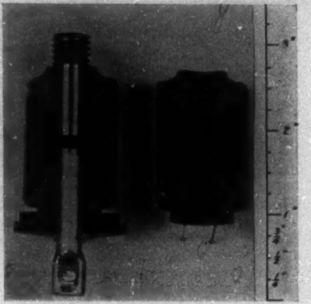

Fig. 4—Section of Compression Chamber of *AF-1* Air Circuit Breaker

In an alternating current circuit, current decreases to zero twice per cycle, providing opportunities for the arc to become unstable and go out. In a direct current circuit on the other hand, there are no such opportunities so that conditions must be established for which the arc is unstable under the conditions of current and voltage occurring in the circuit. There is a strong contrast between this behavior and any deionization that is expected to take place at a current zero only.

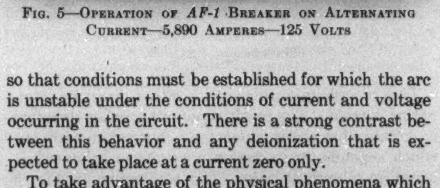

Fig. 5—Operation of *AF-1* Breaker on Alternating Current—5,890 Amperes—125 Volts

To take advantage of the physical phenomena which have been outlined, in producing a circuit breaker a metal cylinder has been taken into which two contacts have been sealed as shown in Fig. 4. The contacts are of course insulated from the metal cylinder and one is free to slide through a packing gland. When these contacts are separated under load or short-circuit current, an arc is drawn in an atmosphere of ordinary air plus metal vapor and some gas from the insulation surfaces. The heat of the arc raises all these gases to high temperature and since the chamber is closed, a high pressure results. Current continues to flow until the pressure builds up to a point where the arc drop is too great to permit a stable arc to be maintained by the available voltage, after which the arc goes out. Such high temperature gas would not ordinarily be considered a good medium to stop an arc. It should be borne in mind, however, that the gases in an arc are always hot. The pressure increase offers an added impediment to the flow of current through gases already hot.

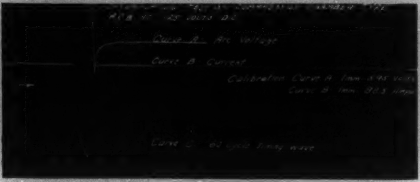

**Fig. 6—Operation of *AF-1* Breaker on Direct Current 4,200 Amperes—125 Volts**

Curve *A*—Arc voltage
Curve *B*—Current
Curve *C*—60-cycle timing wave

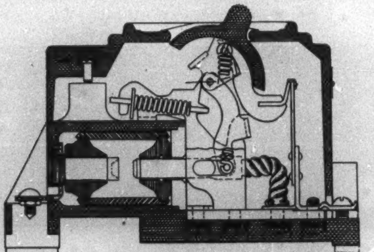

**Fig. 7—Section of *AF-1* Breaker Showing Mechanism and Compression Chamber**

This process takes place with either direct or alternating current. The resulting circuit breaker therefore is suitable for either current as contrasted with one which depends for its action upon deionization subsequent to a current zero. The oscillogram in Fig. 5 shows the interruption of a circuit carrying alternating current. But one-half cycle of current has been permitted, even though tripping of the contacts was produced by the movement of a bimetallic strip heated by the current. Fig. 6 shows corresponding operation on direct current. It can be seen that the drop across the circuit breaker contacts was higher than the impressed system voltage, while current was flowing. This condition, of course, is a prerequisite in interrupting a direct current circuit. A 60-cycle timing wave is included in Fig. 6 to show the duration of the short circuit. For smaller currents, a somewhat longer time is required to build up the necessary pressure, but from the arc characteristics a lesser pressure is required.

It would be very interesting to observe the pressure occurring in these circuit breakers. Such measurements are rendered difficult by the extreme speed of the pressure changes and the small volume of the pressure chamber. Any attachments tend to produce variations in pressure of such magnitude as to mask the phenomena being studied. The cylinders used have withstood the pressures accompanying interruptions at 13,000 amperes, 125 volts, at 60 cycles. At 20,000 amperes, cylinders have failed, indicating pressures of the order of 1,000 lb per square inch.

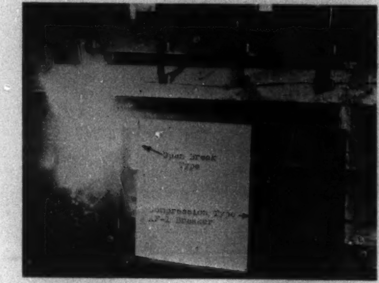

**Fig. 8—Comparison of Circuit Breakers Interrupting 5,000 Amperes at 125 Volts Alternating Current**

The interrupting unit shown in Fig. 4 has been assembled with case and mechanism as shown in Fig. 7. Inasmuch as the interrupting unit is closed completely, it can be recessed in the molded base without vents from which flame and noise might escape and through which foreign material might enter to hamper the operation and circuit clearing functions of the device. The mechanism consists of a simple and sturdy tumbler switch arrangement to which has been added a powerful opening spring held in check by a thermal latch. Under service operations, the circuit breaker may be opened and closed by means of the usual tumbler lever giving snap-make and snap-break. In the event of overcurrent, the thermal strip releases the trip spring and the contacts are forced apart without regard to the position of the operating lever. The mechanism is thus trip free from the operating handle. Such an automatic trip is indicated by a target rather than by a movement of the operating lever so that the opening can not be prevented nor the trip indication obscured by holding the lever. Neither is there a jerk on the lever that might startle an operator closing the circuit on a fault.

The circuit breaker shown has a capacity of 50 amperes at 250 volts and an interrupting capacity rating of 5,000 amperes and will form part of a line of circuit breakers for panel board, building equipment, and general applications employing the compression principle. The full line will include breakers up to 600 amperes, single, double and triple pole, those above the 50-ampere frame size being rated 10,000 amperes interrupting capacity. Fig. 8 shows the relative appearance of the new circuit breaker and a conventional type. The circuit breaker at the left is an open carbon break design; the one at the right, the new *AF-1*. In both cases the circuit interrupted is the same, 5,000 amperes at 125 volts alternating current.

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## Discussion

**C. H. Black:** Reference is made in this paper to a newly-applied principle of circuit interruption which allows no arc, flame, or stream of scorching gases to be liberated. The comparison of these new air circuit breakers with their predecessors is quite striking, as also is the tremendous expansion of the field of air circuit breaker application which these new designs have brought about.

For many years air circuit breakers of the conventional carbon-break, copper-brush-contact type remained in vogue. They are very large and must be mounted on switchboards with the greatest of care to be sure that the exposed arc cannot injure the attendant or damage the panel and adjacent apparatus.

Although many improvements have been effected even the more recent types still require a considerable space for mounting and, when enclosed in a steel housing, weigh a great deal more than breakers of the type described by Mr. Prince. These new breakers have at one stroke achieved a drastic reduction in size and weight, have provided individual enclosure and phase isolation of the arcing contacts, and have retained such improvements as non-oxidizing contacts, trip-free operation, and high speed of contact separation.

A typical breaker of the conventional type, when enclosed in a suitable steel housing, weighs 110 lb with overall dimensions giving a volumetric content of 4,500 cubic inches. The comparable compression type breaker weighs less than 6 lb, with a volumetric content of the enclosing case of less than 160 cubic inches. Furthermore, these breakers may now be mounted in any location, in any position, and as close together as their physical dimensions will permit, without fear of the arc damaging adjacent apparatus, injuring the attendant, or striking between parts of opposite polarity.

Air circuit breakers so small and light, yet retaining relatively high interrupting capacities, must in consequence be relatively inexpensive and hence they naturally tend to supersede not only the earlier and larger circuit breakers but also to supersede fused switches for panel-board and safety-enclosed switch applications. In fact, their design is more or less conventionalized to accord with panel-board and safety-enclosed switch practice and requirements, although the requirements of switchboard mounting also have carefully been considered. Replacing fused switches, these breakers afford more positive circuit protection, decreased maintenance, and more convenient operation. No longer can a penny replace a 15-ampere fuse, nor can the manufacturer's setting of the thermal tripping devices in these new breakers be tampered with unless the entire panelboard is dismantled and the seal on the breaker cover broken. Certainly this insures positive protection. Decreased maintenance naturally results from the ability of the contacts to interrupt severe short circuits many times without requiring attention and from the far greater ease of locating and resetting the breaker that has automatically tripped to clear a fault. There is, too, the greater factor of safety resulting from the elimination of exposed live parts on the front of the panelboard or switch box.

By the use of these breakers switchboards can be greatly reduced in size and in installed cost and yet provide much greater safety of operation. Not only are the breakers themselves totally enclosed but their design facilitates mounting them behind a dead-front steel panel. We find that in some cases it is good economy to sub-divide a relatively few high current circuits and replace the few high-current air breakers with a larger number of the very much smaller and less expensive breakers of the compression type. (This does not, however, recommend the operation of breakers in parallel unless extreme care is taken to insure proper load distribution.)

The application of new breakers of this type to residence wiring is a broad field for which air circuit breakers have not heretofore been considered. Convenience and ease of operation and maintenance obviously are the principal factors justifying the use of air circuit breakers for this application. The complete enclosure of the arc and the totally silent operation of the compression type breaker make it especially adaptable to this class of service where noisy current interruption and visual evidence of arcing (common to most types of circuit breakers) would decidedly be objectionable. When provided with a suitable weatherproof housing, breakers of this type may be mounted out of doors and, if properly applied, may effect quite a decided saving in certain types of power distribution systems.

Beyond these more usual fields of application, breakers of this type and size are being applied to or considered for application to street-lighting systems, auxiliary circuits in electric locomotives, numerous uses in industrial plants, and (when provided with a suitable enclosure) for use in highly explosive atmospheres. The compression type interrupting element also is being considered for application to many other devices for various applications.

It is our belief that the introduction of this new line of circuit breakers not only will broaden the existing field of air circuit breaker application, but will be of immeasurable benefit to the ultimate user because of one or more of these outstanding advantages: greater safety; greater ease of operation and maintenance: reduction in cost of installation; and more positive circuit protection.

**J. B. MacNeill:** Mr. D. C. Prince states that this is a new device operating under a new theory. We cannot agree that Mr. Prince's breaker is new in principle, as a patent covering a construction very similar to the one he uses was issued to the writer in 1926, and the same principle was incorporated in a line of circuit breakers designed in 1929. About that time means was found of introducing effective deionization through plate structures in small capacity units. These plate structures, similar to those in large deion breakers, offer more promise of covering adequately a line of apparatus up to 600 amperes and 600 volts and of eliminating the difficulties encountered. Experience with the compression type showed that the idea of mounting the main contacts completely enclosed in a compression chamber gave rise to maintenance problems, and that the action on low power factor arcs and inductive d-c arcs was not ideal.

**J. Slepian:** The breaker described in this paper is very attractive in that the arc is enclosed completely with the complete suppression of external flame and noise. It is presumed that the capacity of the breaker to interrupt all the ranges of current in all types of circuit to be met in practice has been thoroughly tested by the author. Without questioning the interrupting capacity of the device the following paragraphs discuss the theory of the extinction of the arc in the compression chamber, and particularly the d-c arc.

Increasing the pressure of the gas sufficiently will certainly raise the arc voltage, although other investigators do not record as large an effect as is indicated in Fig. 2 of this paper. Thus, G. P. Luckey, *Physical Review*, IX, 1918, p. 129, for a 0.24-cm arc of 5 amperes between tungsten electrodes in nitrogen gives an arc drop of 54 volts at one atmosphere pressure, but this increases to only 69 volts at 14 atmospheres or 195 lb per square inch above normal. Nevertheless, whether the effect is as large as indicated by Fig. 2 or as small as indicated by Luckey, raising the pressure sufficiently high will raise the arc drop above the supply voltage and therefore will make the arc go out. However, is this the whole story as regards the extinction of the arc in this breaker?

A first doubt is raised by the description of Fig. 3, which states that it applies for a non-inductive circuit. But if the pressure raises the arc voltage above the line voltage then the d-c arc should be extinguished whether the circuit is inductive or not, and the limiting length of arc necessary to interrupt a given circuit at any particular pressure should be independent of the inductance in the circuit. Therefore, does the curve of Fig. 3 apply to an inductive circuit as well, and if not, why not? Incidentally, the curve of Fig. 3 would be much more useful if the current in the circuit were mentioned.

A second doubt is raised by the oscillogram of a-c operation in Fig. 5. Here the arc voltage shown is only a small part of the total supply voltage throughout the half cycle of arcing. But because of the small thermal capacity of the small volume of gas, its temperature, and with it, the pressure should lag very little behind the current, and the high pressure that is counted upon to produce a high arc voltage should have appeared in the first-half cycle. The author himself states that the speed of the pressure changes was so extreme that measurement was rendered difficult. Of course, the arc was extinguished in one-half cycle in the a-c case of Fig. 5 since deionization at the cathode is sufficient at a current zero to interrupt the low voltage, whether high pressure developed or not.

A third doubt is raised by the oscillogram of Fig. 6 showing operation on a d-c circuit. The rapidity with which the current dropped as soon as the arc voltage rose leads to the conclusion that the circuit was only slightly inductive. But in such a non-inductive circuit, the current should have been a maximum when the short-circuit was thrown on, and then should have reduced rapidly as the arc was drawn and the arc voltage rose due to the developing pressure. Actually, however, the current rose rapidly to less than half its maximum, and then increased slowly to its maximum over nearly a cycle and one-half of the timing wave and then very suddenly fell to zero. Such a course of the current in a slightly inductive circuit is not consistent with a continually increasing arc voltage; and suggests that the arc voltage remained low for more than a 60th of a second.

Unfortunately, the zero line of arc voltage, and with it the first period of arcing has been cut out of Fig. 6, but what is left of the oscillogram does indicate that the arc voltage did remain low for a considerable time. The only alternative would be that the contacts remained closed for a long time, which is not consistent with the fast operation shown by Fig. 5. The writer asks the author if the arc voltage did remain low for some time, and why the high pressure did not raise the arc voltage at once?

The writer makes the following suggestion. Under the influence of the intense magnetic field accompanying the heavy current, the gas space will be thrown into a violent turbulent flow. At a particularly favorable moment in this flow the arc voltage might be raised momentarily, which, in a non-inductive circuit would cause a quick drop in current. We would then have a smaller current arc in the still persisting turbulence produced by the preceding larger current, and this would call for a still higher arc voltage, which would further reduce the current, and so the arc would be extinguished. This suggestion would fail however, in an inductive circuit since with the current decreasing slowly, the turbulence also would die down and the high arc voltage would be lost. This suggestion also would make the arcing time in the non-inductive circuit a somewhat random affair, depending on the occurrence of a fortuitous moment of high arc voltage. Do the arcing times in a particular d-c circuit show random variations in length?

Another suggestion is that the high arc voltage appears when the arc blows to a side, and bears against the insulating bushing at the ends of the chamber. The material of which these bushings is made is not mentioned in the paper, but if it is organic, then under the heat of the arc it will give off gas at a high rate producing a flow which will extinguish the arc. This suggestion also will fail in an inductive circuit, since the continued evolution of gas from the bushings for a long period of arcing will quickly burst a tight chamber.

Since both these suggestions fail in an inductive d-c circuit, may I ask the author whether there is any limit to the inductance at which the breaker begins to fail.

For both suggestions, the high pressure developed will be a favorable influence. We should expect the turbulence in a denser gas to have a greater effect on the arc voltage, and also the turbulence should persist longer after the current starts to decrease.

**H. R. Summerhayes:** The development of the compression type low voltage air circuit breaker with its compactness, high rupturing capacity and ease of making it totally enclosed or weatherproof, brings to mind a new field in which such circuit breakers might be used.

Outside of the existing low voltage alternating current networks, there is still a considerable field of distribution, residential and commercial, covered by systems of the strictly radial type, in which each distribution transformer serves a separate secondary main of its own, the mains served by adjacent distribution transformers not being connected.

It has been realized for a long time that by connecting these mains or banking the transformers, the voltage regulation and load distribution would be improved, but one of the disadvantages that prevents the more frequent use of banking is the difficulty of obtaining sufficiently selective fuses for use in the secondaries of the transformers. It is suggested that by the use of this type of circuit breaker with its thermal tripping arrangement, which could be adapted to the thermal overload capacity of a transformer, there will be sufficiently selective action to permit the banking of transformers on a single secondary without the disadvantages attending the use of secondary fuses.

It is believed that with such circuit breakers on the secondaries of each transformer, a short-circuited transformer could be cut out of the system by the primary fuses and the secondary circuit breakers without opening the secondary circuit breakers or primary fuses of the other transformers banked on the same secondary; thus no interruption to the service would be caused by trouble in the transformer.

Whether such an installation would be advisable is a matter of study for the distribution engineers, but it is offered as a means of improving service and realizing the advantages of banking transformers.

**D. C. Prince:** Mr. C. H. Black has discussed the new compression circuit breaker from an application point of view. His remarks are particularly timely as no description of a device is complete without the background into which it fits.

Mr. J. B. MacNeill called attention to various structures purporting to be compression circuit breakers known before the device described in the paper. One notable difference was present, however. Mr. MacNeill's circuit breakers were all provided with vents allowing the escape of pressure. At low currents, these vents prevent the accumulation of sufficient pressure to give positive operation, while at high currents a scouring action takes place which greatly reduces the useful life of the device. The underwriters call for permanently sealing the entire interrupting element and mechanism of these small circuit breakers. The contacts therefore are entirely inaccessible whether sealed or not. By definitely sealing the contacts they are less susceptible to dirt and other deteriorating influences so that maintenance is much less likely to be required than in other types of small circuit breakers.

Doctor J. Slepian presumes that these circuit breakers have been thoroughly tested. That is correct. The ratings of these devices are such that capacity is available for full power testing of even the largest units in the line and that has been done.

Doctor Slepian asks whether the curve in Fig. 3 would be changed were the circuit inductive. It is general knowledge that a longer arc can be maintained with an inductive circuit, other things being equal. This is because self-induced voltages may add to the impressed voltage, providing momentarily a high voltage to maintain the arc.

In the operation shown by the oscillogram of Fig. 5, some time was required for the thermal strip to release the mechanism and for the contacts to part; this accounts for the delayed appearance of arc drop on the film.

Doctor Slepian's statement that 125 volts is insufficient to maintain an a-c arc is not true in general since alternating current arcs are maintained with less voltage than this.

In Fig. 6 as in Fig. 5, time was required for the circuit breaker to trip and separate its contacts after which the counter emf rose quickly and the arc was extinguished.

Doctor Slepian's magnetostrictive theory is very interesting; however, it is observed that the effect of inductance merely is to lengthen the arcing time rather than cause failure to interrupt. There are differences in behavior with different materials. These differences appear to be related to the pressure generating properties of the material but not to their magnetic properties.

Much more work remains to be done on the theory of operation of the compression breaker and to that end Doctor Slepian's suggestions are very much appreciated. Thanks to adequate testing facilities, the performance of these circuit breakers is entirely independent of the proof of the theory.

# Arc Extinction Phenomena in High Voltage Circuit Breakers—Studied With a Cathode Ray Oscillograph

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***Synopsis.***—*A medium-speed cathode-ray oscillograph with a rotating film has been built for the study of circuit breaker transients. The film is wrapped around a drum and rotated in the vacuum at high speed. Each film shows in a continuous trace a complete story of the formation of arc, subsequent reignitions, and final extinction. More than 15 complete cycles may be recorded without excessive blurring. Each film is self-calibrated. A study of several types of circuit breakers with this instrument shows that the nature of the transients at time of arc extinction varies with the type of breaker on test. Different types of breakers tested on the same circuit have different rates of rise of recovery voltage. The deionizing efficiency of a breaker influences not only the arcing time, but the transient oscillation at current zero. The influence of the deionizing efficiency of the breaker upon the stability of the decreasing arc current near current zero is studied and interesting conclusions made.*

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## INTRODUCTION

THE role played by the circuit constants in all types of interrupting devices has been brought to the attention of electrical engineers only in the last few years.[1] The cathode ray oscillograph is the instrument that has made possible the study of arc transients in circuit interrupters. A new type of cathode ray oscillograph has been built that is adapted especially for all types of investigations involving frequencies of from 25 cycles per second to 200,000 cycles per second. This oscillograph has been the means of securing much new information about arc phenomena in circuit interrupters. It is the purpose of this paper to describe this instrument used in a study of circuit breaker arc transients around current zero and to discuss the results obtained as applied to circuit breakers.

## APPARATUS

In a study of transients in circuit breakers at current zero a cathode ray oscillograph is necessary. The difficulties encountered in synchronizing the cathode ray oscillograph with the current zero previous to interruption are many because of the variable arcing time of a breaker. Many oscillographs lose from 10 to 50 per cent of the wave front in tripping the beam and therefore give no information on the voltage across the breaker before current zero. These troubles were eliminated by using a rotating film oscillograph. Dufour[2] first used the rotating film in a cathode ray oscillograph. This oscillograph was adapted a few years ago for lightning investigations.[3] Other better designs have since replaced it.

An early type of rotating film cathode ray oscillograph was rebuilt for the investigation of circuit breaker phenomena. Cone joints were replaced with flanges and rubber gaskets. A high-speed motor was designed to turn the film at a maximum speed of 7,200 rpm. Vacuum seal is made by a monel cup through the air gap in the driving motor. A d-c generator supplies high voltage for the electron beam Fig. 1a); the beam is focused on the film by a concentrating coil. A 15-mil diameter pinhole anode narrows the beam to a very fine trace on the film.

A wiring diagram of the test circuit is shown in Fig. 1. A Norinder relay is used to trip the beam onto the film. Voltage is applied to the Norinder relay plates by a multi-contact relay which in turn is energized through mechanical contactors mounted on a cam shaft (Fig. 1b). Other contactors mounted on the same shaft control the entire test operation, being adjusted to give proper timing and sequence. Interruption of the relay coil current removes the voltage from the Norinder relay plates and grounds them.

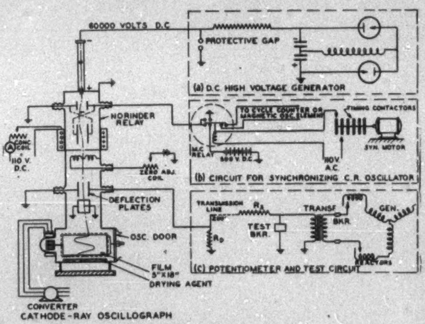

FIG. 1—CATHODE RAY OSCILLOGRAPH CONNECTIONS FOR CIRCUIT BREAKER TESTS

It is possible to set the contactors on the cam shaft so that the beam will be on the film for 1 or 20 cycles. Normally from 5 to 8 cycles are necessary in testing circuit breakers.

The high-speed 3-phase motor used to drive the film is fed from a converter. Speed of the film is controlled by resistances in the armature and field of the stator in the converter. The maximum speed of 7,200 rpm draws out a 60-cycle wave to a length of 36 in. on the film. This speed corresponds to a uniform timing sweep of

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

[1] For references see bibliography.

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180 microseconds per centimeter. The film is 5 inches wide and 18 inches long. By rotating the film at a speed out of phase with the 60-cycle wave on the deflection plates, it is possible to record 15 or more complete cycles without excessive blurring.

Voltages for the deflection plates are reduced by resistance potentiometers as shown in Fig. 1c. Non-inductive water-tube resistors are used throughout. The resistor tubes are filled with distilled water, then brought to the proper resistance by the addition of salt. An overhead transmission line leads into the oscillograph room through roof bushings from the contacts of the circuit breaker about 200 feet away. Spurious oscillations in this transmission line are prevented by grounding through a resistance equal to the surge impedance of the line. The series resistance, $R_s$, is varied to give the proper deflection for different test voltages.

An element on the magnetic oscillograph can be used to show when the cathode ray oscillograph operates. By allowing a cycle or two of restored voltage on the cathode ray film each oscillogram automatically is self-calibrated. Ten minutes are required to break the vacuum, reload the oscillograph, develop the film and pump out ready for the next test.

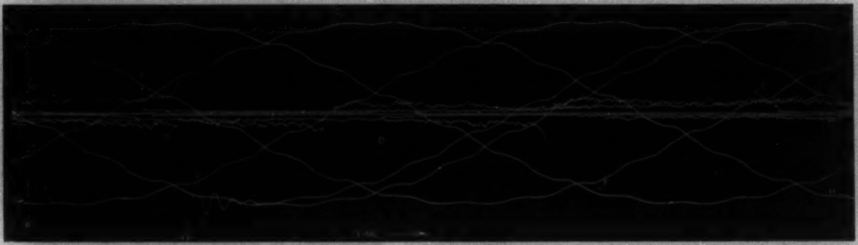

Fig. 2

This oscillograph may be used with a stationary film as well as with the rotating film. To change from the rotating film to the stationary film a small injector is inserted into the shaft and is connected mechanically to a hexagonal knob in the oscillograph door. The stationary film has 6 exposures of film 5 in. by 3 in. in size. The operation of this oscillograph is so simple that a laboratory worker learned to operate it on circuit breaker tests after observing a few tests. The cathode ray oscillograph has now become a part of the routine testing equipment for circuit breakers. Many different types of electric devices have been tested including fuses, oil and air breakers, lightning arresters, gaseous discharge tubes, rectifiers, and vacuum switches.

Fig. 2 shows a typical oscillogram of the operation of a plain-break, butt-contact oil breaker at 13,200 volts. The speed of the film is 750 microseconds per inch, while the sensitivity of the deflection plates is 8,000 volts per inch. The test current was 1,300 amperes.

Referring to Fig. 2 at point *A*, the contacts were closed and no voltage appears on the deflection plates, a zero line is traced. The time scale increases to the right across the film. At point *B* the breaker is opening its contacts and the first reversal of current takes place. At the right edge of the film the trace is interrupted to begin again on the left edge *K′K*. As the contacts continue to open each succeeding reignition voltage, *C*, *D*, *E*, *F*, *G*, *H*, *I*, gets higher until at *J* the arc is extinguished and the recovery voltage rises on a transient to the open circuit voltage.

A calibration of the speed of the film is obtained by measuring the distance on the zero between two successive crossings of recovery voltage. The deflection sensitivity is determined directly from the film by (1) reading the recovery voltage from the magnetic oscillograph voltage element; (2) the plate sensitivity multiplied by the potentiometer ratio.

From the magnetic oscillograph element showing the rate of separation of contacts it is possible to determine accurately the rate of recovery of dielectric strength in the space between the breaker contacts. The oscillogram also shows the variations in arc voltage accurately and in greater detail than the magnetic oscillograph. Overshooting, frequency and rate or rise of recovery voltages are easily measured from this film.

## Observed Phenomena

The phenomena which occur during the interruption of high-voltage, high-current circuits have been the subject of much investigation and study but it is only since the cathode ray oscillograph has been applied to this work that accurate detailed data can be obtained concerning it. With the high power testing facilities and cathode ray oscillographs now available it is possible to record these phenomena at powers that are encountered in service, and to show variations in the phenomena that last only a few microseconds. The use of these facilities for the study of arc extinction has resulted in an advance in our knowledge and a modification of previous theories of arc extinction as described in this paper.

Since this equipment became available, it has been used extensively during tests on many different sizes and types of circuit breakers from 15 kv to 230 kv at various currents from 200 to 100,000 amperes. The tests were made on plain-break oil circuit breakers, deion grid oil circuit breakers, and deion air-break circuit breakers. With this wide variety of conditions, the following facts were soon noted:

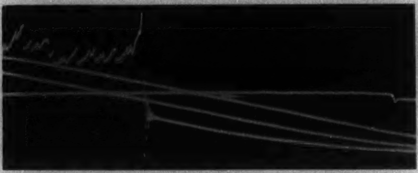

Fig. 3—Oscillogram of the Interruption of 14,000 Amperes at 7,600 Volts, Single Phase

1. The rate of rise of recovery voltage, which appears across the breaker contacts at the time of arc extinction is a function, not only of the circuit but also of the circuit breaker.
2. The nature of the transient, which occurs at the time of arc extinction, depends on the breaker as well as on the system.
3. The voltage at the end of the last half-cycle of arcing has various characteristics governed by the current, circuit characteristics, and breaker.

## Discussion of Observed Phenomena

The most important sections of 4 typical oscillograms are reproduced in Figs. 3 to 6 to illustrate the particular features on which these observations of interrupting phenomena are based. In this paper, detailed comparisons will be drawn to demonstrate the facts already stated, and careful analyses made to give the magnitudes of the quantities involved.

That the rate of rise of recovery voltage is influenced by the breaker is shown in Figs. 3 and 4. These oscillograms, both typical of their respective series, were taken on the same circuit, with the same generator connections, with the same bus structure to the same test cell, with practically the same reactor connections and with the same measuring and recording instruments, but with different breakers. The oscillogram in Fig. 3 shows the interruption by a deion grid breaker of 14,000 amperes, 7,600 volts, single phase, with voltage rising across the contacts after the zero of current at an average rate of 2,080 volts per microsecond. The oscillogram in Fig. 4 shows the interruption by a plain-break breaker of 12,000 amperes, 7,600 volts, single phase, with a maximum rate of rise of recovery voltage of 500 volts per microsecond and an average of about 170 volts per microsecond up to 6,500 volts. In other words, with all conditions external to the breakers the same, the rate of rise of recovery voltage varied in the ratio of 1 to 12 for two different breakers. The breakers caused this difference.

These 2 oscillograms show that not only the magnitude but also the nature of the transient after the zero is influenced by the breaker and varies even though the rest of the circuit is the same. Fig. 3 shows the voltage varying in a very complicated manner during the transient. A careful analysis discloses that there are three principal frequencies of approximately 91,000, 39,600 and 10,100 cycles per second. During this test the voltage reaches a peak 1.88 times the instantaneous generated voltage. On the other hand, Fig. 4 shows the voltage varying in a very simple manner and having a peak value of only 1.14 times the instantaneous generated voltage. Fig. 5 is a reproduction of a cathode ray oscillogram showing a transient produced in another laboratory by a plain-break circuit breaker interrupting 8,700 amperes at 7,600 volts. The transient appearing in this test varies in a manner having characteristics similar to each of the two previously described. It is mainly an oscillation of 17,000 cycles, with a relatively low amplitude and peak voltage about 1.4 times the instantaneous generated voltage. These three transients of quite different appearance, must be related since all occur on tests of comparable voltage and current.

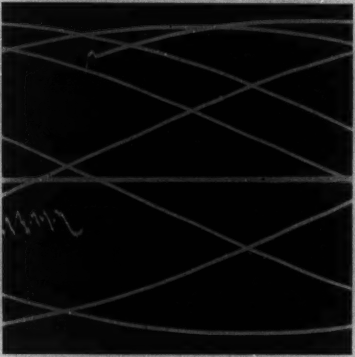

Fig. 4—Oscillogram of the Interruption of 12,000 Amperes at 7,600 Volts, Single Phase

The nature of the phenomena which occur just before the voltage becomes zero at the end of the last half-cycle of arcing also varies, as shown by these same oscillograms. In Figs. 4 and 5 the arc voltage becomes steady and then decreases in a smooth curve to zero. In Fig. 3 the arc voltage rises in a somewhat irregular line to a peak value and then decreases very rapidly to zero.

Fig. 6 shows an oscillogram of a 44,000-volt, 330-ampere interruption in which the arc voltage increases slightly for a short period in an irregular line, similar to the one in Fig. 3, and then more rapidly in what appears to be part of a sinusoidal wave that forms the main part of the transient after the zero of voltage. It appears then that these variations in characteristics occur before as well as after the voltage becomes zero.

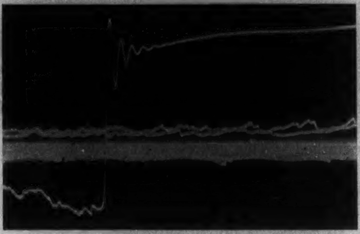

FIG. 5—OSCILLOGRAM OF THE INTERRUPTION OF 8,700 AMPERES AT 7,600 VOLTS, SINGLE PHASE

These 4 oscillograms are typical of different types of interruption that are obtained in oil circuit breakers. The phenomena shown on them appear quite different in the extreme cases but long testing experience indicates that between these extremes are intermediate cases which divide the differences into small steps and show that they are all closely related. Consequently, a satisfactory theory of the phenomena of arc extinction must explain each of these cases.

The theories of the manner in which alternating-current arcs in circuit breakers are extinguished can be tested by these cathode ray oscillograms. Some of these conceptions contain approximations calculated to eliminate variables believed to be of minor importance; others have been constructive attempts to explain the phenomena by means of theoretical considerations; all have been based to some extent on assumptions. Now, in the light of additional data on these phenomena, the ideas should be reviewed for verification or modification.

Heretofore it has been assumed that up to the time of current zero the effective resistance of the arc space is negligible. This is admittedly only a simplification but in most discussions of heavy-current arcs in high voltage circuits, it is accepted and the phenomena during this period are neglected. However, it is at this time that the ionizing and deionizing processes are active in setting up the conditions that produce the observed voltage variations prior to voltage zero. These processes also determine whether the current zero occurs before or simultaneously with the voltage zero. Therefore, the period while current is flowing in the arc should not be neglected. Although the arc path is to be studied, the actual cross sections and corresponding densities of ionization which are continually changing, fortunately do not have to be determined, since the overall conductivity of the arc space can be calculated from the records of the cathode ray and magnetic oscillographs.

In this paper, the quotient of the voltage across the breaker divided by the current through the arc is called the effective resistance. From the usual arc voltage characteristic for stable conditions it is evident that the effective resistance of the arc path increases as the current decreases. This can be seen also in Fig. 7 which shows arc characteristics for various conditions.[4] Curve *A* represents the characteristics of an arc in equilibrium, that is, when the current changes so slowly that the ionizing activity always just balances the deionizing activity. When the current is increasing very rapidly, the voltage for a given current is greater than for a stable arc of the same current since the total number of ions present corresponds to a lower current value. The characteristics of such a current are shown by curve *B*. On the other hand, if the current is decreasing rapidly, the ionization is greater than it would be for stable conditions and the characteristics are similar to curves *C*, *D* or *E* depending on the rate of change of current and the rate of deionization. These curves correspond to the characteristics shown in Figs. 3, 4 and 5 and indicate that the effective resistance may vary greatly as the current approaches zero.

Moreover, it is possible for the effective resistance to become infinite before the current in the inductive part of the circuit, the generators, transformers, reactors, etc., becomes zero. This has been shown for small powers with arcs in air between metal plates by Messrs. Attwood, Dow and Krausnick.[5] The same phenomenon is shown for 44,000 volts, 330 amperes, in Fig. 6. This phenomenon occurs when the arc becomes unstable and the current in it suddenly shifts to another parallel circuit, in these cases a small parallel distributed capacity of the conductors and equipment. Since the cur-

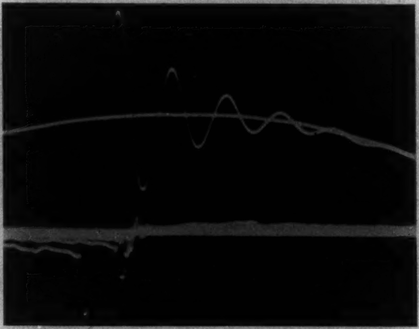

FIG. 6—OSCILLOGRAM OF THE INTERRUPTION OF 300 AMPERES AT 44,000 VOLTS, SINGLE PHASE

rent in the inductive part of the circuit is still flowing, it charges the capacity, causing a rise in voltage which is a function of the current flowing when the arc was extinguished, the rate of change of voltage at that time, and the capacity between lines. This capacity also exerts an important influence in determining the time when the arc will be extinguished because, if the voltage is increasing between the contacts, a charging current flows which reduces the current in the arc and facilitates the extinction.

From these typical oscillograms it can be concluded that the rate at which the current is approaching zero, the rate of deionization, and the circuit characteristics are of great importance in arc extinction. The effective resistance of the arc space is increasing as the current approaches zero and it may have a relatively low value, a relatively high value or even be infinite when the current in the main part of the circuit reaches zero.

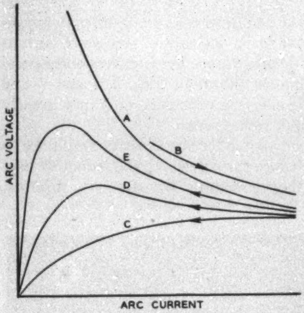

FIG. 7—STATIC AND DYNAMIC ARC CHARACTERISTICS

The phenomena immediately after this zero must also be considered. There has been a generally accepted idea that at the end of the last half-cycle of arcing the current comes to zero and that no appreciable current flows thereafter in the reverse direction. If this were true, the phenomena after this instant would be independent of the influence of the circuit breaker and would depend only on the constants of the circuit. With these conditions the oscillograms reproduced in Figs. 3 and 6 would be typical. However, Figs. 4 and 5 are different and could not be produced on these circuits if this assumption were true. The voltage rise in Fig. 4 is similar to the increase in voltage across a resistance in a series circuit consisting of a resistance, an inductance, and a suddenly applied emf. If a variable and rapidly increasing resistance is assumed, then the voltage phenomena are even more similar. Moreover, if a capacity is added in parallel with the variable resistance, the voltage varies in a manner similar to Fig. 5 also. Since the oscillograms are records of the voltage across the terminals of the breaker, this rapidly increasing resistance must be sought within the breaker itself.

As has been discussed already, the effective resistance of the arc path is a variable and increases rapidly as the current approaches zero. In oscillogram 4 the current reaches zero at the end of the last half-cycle of arcing while the effective resistance of the arc path still is relatively low. If the resistance continues to increase at rates comparable to those at which it was increasing prior to current zero, it has characteristics which permit of the passage of sufficient current to modify the voltage phenomena. Moreover, the resistance increases so rapidly that the current ceases to increase in a few microseconds and is reduced to zero without the arc restriking.

A very useful conception, advanced by Doctor Slepian, is that the increase in dielectric strength between the contacts must be more rapid than the increase in voltage across the breaker if the arc is to be extinguished.[1] This generally has been interpreted to mean that no appreciable current flows after the current reaches zero unless a complete breakdown into an arc occurs and another half-cycle of power current flows. This, of course, is not in agreement with the oscillograms which indicate that relatively large currents may flow for a few microseconds. The more recent definition recognizes the possibility of this current flowing. Doctor Slepian has defined[6]—"the dielectric strength or breakdown voltage at any particular instant as that particular voltage which, if it were suddently applied, would cause the resistance of the arc space to stop increasing, and such that if a larger voltage were suddenly applied, the resistance would decrease."

The arc extinction still can be considered as a race between the dielectric strength and the recovery voltage but, with the condition of current flowing during the time of voltage rise, the two are not independent since the current that flows retards the deionization and increase of resistance, and also modifies the rate of rise of the recovery voltage. The phenomena of arc extinction in a circuit breaker, as typified by these 4 oscillograms, can all be explained by a deionizing action that starts to be effective before the current reaches zero and which increases continuously the effective resistance of the arc space. This effective resistance may become infinite before the current in the main part of the circuit becomes zero and the result is similar to the operation shown in Fig. 6. It may become infinite at approximately the same time as the current in the main part of the circuit becomes zero and the result is similar to the operation shown in Fig. 3. If, however, the arc space still has a relatively low resistance at this time, the current will reverse and flow for a very short time giving an operation similar to that shown in Fig. 5 or for a longer time with an operation similar to Fig. 4. However, if the current flowing after the zero becomes too great the rate of ionization will exceed the rate of deionization, the conductivity will increase and the arc will restrike for another half-cycle. The arc extinction phenomenon is, therefore, a process of deionization, the important part of which may extend over a period from about 100 microseconds before the zero of current to about 100 microseconds after the zero, with the critical time in most cases occurring within a few microseconds of the zero. The factors controlling it are the rate of decrease of current, the rate of deionization, the circuit constants and the generated voltage.

## ANALYSES OF OSCILLOGRAMS

The exact relation which exists between voltage, current, effective resistance and time can best be studied by making detailed analyses of oscillograms. Since the 4 reproduced in Figs. 3 to 6 are typical, they are used to demonstrate the salient points.

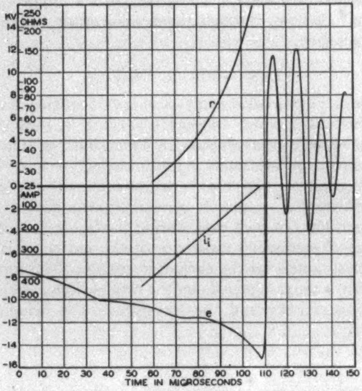

FIG. 8—ANALYSIS OF THE OSCILLOGRAM IN FIG. 3

The oscillogram shown in Fig. 3 is plotted in Fig. 8 from careful measurements. The current flowing in the arc is determined when the rate of change of current and the time of zero current in the arc are known. These can be calculated from the records in the following manner. The rate of decrease of the current flowing in the arc can be found from the magnetic oscillogram and from the relation

$$\frac{di}{dt} = \frac{e}{L} \tag{1}$$

Where $e$ = the voltage drop across the inductance of the circuit.

$L$ = the magnitude of the inductance.

The instant at which the current reaches zero can be determined in the following way from the cathode ray oscillogram. Since the voltage prior to the negative peak is rising steadily but less rapidly than it decreases after the peak, the current still is flowing through the breaker up to the time of the negative peak. Moreover, since the oscillations after the negative peak can be broken down into 3 damped sinusoidal waves with frequencies of 91,000 cycles per second, 39,600 cycles per second and 10,100 cycles per second, having the start of these oscillations coinciding with the negative peak of voltage, the current is not flowing for any appreciable interval of time after the negative peak of voltage. Therefore, the zero of current in the arc corresponds closely with the negative peak of voltage and the curve of current is determined for this case. The effective resistance at any instant is the quotient of the voltage divided by the current and these values are plotted, to a logarithmic scale.

This oscillogram is rather unusual in that the negative peak of arc voltage is very high, 15,200 volts, Fig. 3. The high arc voltage during the last half cycle increased the rate of change of current so that the extinction took place with the relatively low instantaneous generated voltage of 3,900 volts corresponding to a power factor of 90 percent. Even with this condition, the rate of rise of recovery voltage was 2,080 volts per microsecond. As the current during the short circuit was limited only by the breaker and the reactance of the generator and reactors, the power factor of the circuit was actually 10 per cent or less.

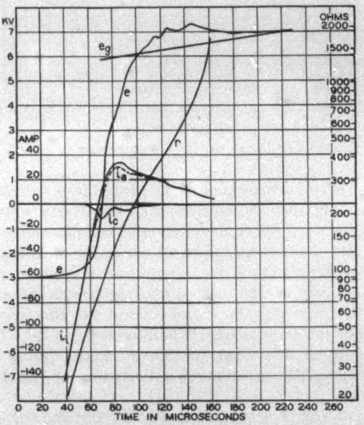

FIG. 9—ANALYSIS OF THE OSCILLOGRAM IN FIG. 4

The oscillogram of Fig. 4 is copied in Fig. 9. Since the arc voltage approaches zero without having a negative peak, the characteristics are similar to curve $C$ of Fig. 7, the arc space is conducting at the time of zero voltage, and the current and voltage become zero simultaneously. The rate of change of current is determined from the magnetic oscillogram and the constants of the circuit as in the previous case. The effect of the capacity in parallel with the breaker should be considered in this oscillogram although it has been neglected in the first as it does not appreciably change that result. The discharge of this electrostatic capacity increases the current in the arc by causing a current which is proportional to the magnitude of the capacity and the rate of change of voltage. This current is plotted as $i_c$ in Fig. 9. The arc current, $i_a$, can now be plotted as the sum of $i_l$, the current flowing through the generator and reactors, and $i_c$. As the conductivity of the arc space is relatively high at this time, the rapidly rising voltage starts the current in the reverse direction without perceptible pause.

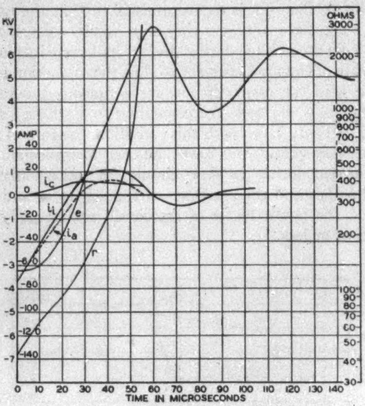

FIG. 10—ANALYSIS OF THE OSCILLOGRAM IN FIG. 5

The effective resistance of the arc has been increasing but is only about 90 ohms at the time of zero voltage. By using the formula (1) for currents after as well as before zero and by making an allowance for the damping of the circuit, the current $i_l$ after the voltage goes through zero can be plotted and appears as shown in Fig. 9. From this the current $i_a$ and the effective resistance can be plotted. It is interesting to note that the current that flows in the arc space during the transient after zero reaches a maximum of about 30 amperes.

Fig. 5 has been plotted in Fig. 10 and the currents and resistance calculated as for Fig. 9. In this case, the current in the breaker after the zero of voltage reaches a magnitude of 12 amperes but decreases rapidly to zero.

These 3 oscillograms are for approximately the same currents and voltages so they can be compared directly. In Fig. 8 the resistance increases from 30 to 300 ohms in 40 microseconds, during which time the current decreases from 360 amperes to approximately zero. In Fig. 9 the resistance changes over the same range in approximately 62 microseconds with an average current of about 30 amperes flowing which indicates a much slower rate of deionization. In Fig. 10 the resistance changes over this range in about 52 microseconds with an average current of about 30 amperes, but the value at the time of zero voltage is somewhat higher than for Fig. 9 and the increase is more rapid above 300 ohms.

Fig. 11 is made from the oscillogram of Fig. 6 with the currents calculated as in the preceding cases. Since this is a 330-ampere, 44-kv test, the arc is longer and the resistance higher than in the other oscillograms. At time $t = 145$ microseconds the resistance is 1,100 ohms and the current about 10 amperes. At this point, the arc is extinguished suddenly and the voltage across the breaker terminals rises as the electromagnetic energy in the circuit becomes electrostatic. This is the beginning of the sinusoidal transient. No current of any appreciable magnitude flows through the breaker after the arc is extinguished.

## DISCUSSION OF RESULTS

From the preceding analyses, it is evident that these 4 oscillograms having transients varying in form from complicated waves composed of 3 sinusoidal oscillations to simple, approximately logarithmic, curves and varying in magnitude over wide ranges even with the same circuit conditions, are in general aspects similar and comparable. In each case, during the last half-cycle of arcing, the effective resistance of the arc space is increasing rapidly as the current decreases. The rate at which it changes depends on the rate of decrease of the ionizing activity and the strength of the deionizing activity.

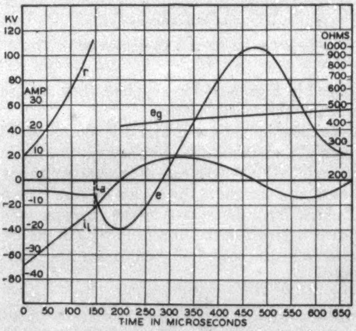

FIG. 11—ANALYSIS OF THE OSCILLOGRAM IN FIG. 6

The character of the transient is determined by the magnitude and rate of change of the effective resistance. If it is high and increases rapidly, the current after reaching a small value may suddenly cease flowing through the arc before the current in the rest of the circuit becomes zero. In such a case the electromagnetic energy in the circuit changes to electrostatic energy by raising sinusoidally the potential across the capacity in parallel with the breaker, thereby causing the zero of voltage to occur several microseconds after the zero of arc current. In other oscillograms the effective resistance becomes high as the arc current approaches zero but the arc exists up to the time of the voltage peak, which is approached in an irregular line. In those cases that have relatively low effective resistances at the time of zero current, the arc voltage prior to the zero becomes smooth and has little or no peak. The voltage and current reverse directions simultaneously. Analyses of oscillograms from a long period of testing indicate that the current after the zero can reach values up to 30 amperes and that these currents can modify the transients and reduce the rate of rise of recovery voltage in some cases to a fraction of what it would have been had no current flowed after zero. In still other cases in which the circuit characteristics normally would cause a low rate of rise, the current drawn by the breaker has little effect on the voltage.

It has been shown many times[7-12] that the severity of the interrupting duty imposed on a circuit breaker varies with the circuit characteristics. However, the rate of rise of recovery voltage can not be used in all cases as a criterion of the circuit characteristics, since it has been shown that the breaker can modify this value. Moreover, this reduction in the rate of rise of recovery voltage does not make the circuit easier to interrupt. In fact, the oscillograms show that the breaker producing this effect actually is carrying appreciable current which is retarding the deionization of the arc space, and that this current, if it becomes too large, will cause reignition of the arc. A breaker, which has a weak deionizing action and passes current so as to reduce appreciably the rate of rise of recovery voltage, is not being subject to light duty but actually is operating in a range where its ability to interrupt the circuit is rather uncertain.

With the rate of rise of recovery voltage a function of both the circuit and the circuit breaker, the conclusion may be drawn that until much more experimental data are collected and analyzed to show the relations which exist for various types of circuit breakers, any attempt to specify the rates of rise of recovery voltage to which breakers are to be subjected on test, or any attempt to make quantitative comparisons between different conditions of test is futile.

### CONCLUSIONS

In conclusion, these results may be summarized in the following statements:

1. Arc extinction depends on the deionization which takes place both before and after the current zero.

2. The effective resistance of the arc space increases in a curve which is a function of the rate of deionization.

3. The effective resistance may become several thousand ohms several microseconds before or after the zero of voltage.

4. The rate of rise of recovery voltage is a function not only of the circuit but also of the circuit breaker.

5. The specifying of certain rates of rise of recovery voltage for circuit breaker testing is not advisable at the present time.

This paper has presented some of the interesting circuit breaker phenomena which it has been possible to study by means of the cathode ray oscillograph. The subject has not been exhausted and it is believed that the continuation of the work will lead to a better understanding of the effects of circuit characteristics on circuit breaker operation.

### ACKNOWLEDGMENT

The authors wish to thank those who have aided them in their work, Doctor J. Slepian for his counsel on arc phenomena, Mr. O. Ackermann for his advice on cathode ray oscillography and Mr. H. M. Wilcox for his assistance in the preparation of this paper.

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## Discussion

**J. B. MacNeill:** The paper presented by Messrs. Van Sickle and Berkey is the result of research work on the effect of restored voltage characteristics upon circuit breaker action. With the increased knowledge of restored voltage conditions, the suggestion has seriously been made that this factor should be taken into account in each application of high voltage oil circuit breakers. It is known that the rates of voltage restoration vary from low values, say, 150 volts per microsecond, up to as high as 4,000 volts per microsecond on commercial circuits, and that certain freak circuits may go even higher.

Investigation has shown, however, that modern circuit interrupters minimize the effect of this wide range of restored voltage upon the breaker action, and that the time of arcing does not increase to any such extent as does the rate of voltage recovery. Furthermore, it has been found that the circuit breaker construction itself affects radically the rate of voltage restoration; and this discovery, together with an analysis of the reasons therefore, is the principal contribution of the Van Sickle-Berkey paper, made possible by the improved cathode ray oscillograph they describe.

Since modern improved circuit breakers minimize the effect of voltage recovery in their action, and since it is reasonable to make circuit breakers that will take care of conditions encountered in service without added cost, it seems undesirable to introduce this factor into every day circuit breaker application. It is recommended, therefore, that the manufacturers give their customers the necessary assurance that their equipment will meet the required conditions without introducing complicated calculations that are of doubtful value in applications. For the future it will be obvious that more must be known of this subject; and that the manufacturers will wish to adapt their designs, where necessary, so that efficient circuit interruption may be accompanied by breaker action as beneficial as possible on the restored voltage characteristics of the system.

**D. C. Prince:** This paper presents observations made by the aid of the cathode ray oscillograph with rotating film. With this arrangement, the spread of the time axis is limited by the maximum possible film speed. Mechanical contactors mounted on the shaft of a synchronous motor provide for a sequence of oscillograph and circuit breaker operation that gives the desired oscillograph record. The long moving film makes it possible to record the operation of plain-break oil circuit breakers that are for an indeterminate number of half cycles. Similarly, the moving film method appears to be advantageous in observing a circuit breaker that has a high arc drop prior to the current zero, where there is no sharp transition between arc voltage and recovery voltage which can be used for tripping purposes.

As a result of the observations that have been made by the use of this instrument, the authors have concluded that circuit breakers may influence recovery rates to such an extent that circuit recovery rates can not be incorporated in circuit breaker standards. Most of the data shown apply to plain break oil circuit breakers that notoriously are erratic in performance and are at the same time known to be sensitive to circuit recovery rate conditions. The modification produced in the circuit recovery rates by these breakers is due to their attempting to clear the circuit at times other than the normal current zero, or to conduction of small currents without a complete breakdown of the dielectric. These characteristics tend to produce distress in the circuit breaker as it is required to absorb energy normally stored in the electric circuit.

The single film showing the operation of a deion grid circuit breaker shows no indications that current flowed after the current zero at which current interruption occurred. The form of the recovery voltage oscillation appears quite normal and does not seem to have been influenced by the breaker characteristics, except that due to the rather high arc drop just prior to the current zero, the amplitude of the oscillations is considerably larger than it would otherwise have been.

For comparison with these records, attention is called to the cathode ray films shown by Messrs. R. M. Spurck and H. E. Strang.[1] In these records no appreciable arc drop appears prior to the current zero at which interruption occurred and it was therefore possible to trip the cathode ray oscillograph by the recovery voltage itself. No appreciable current flowed subsequent to the current zero at which the circuit was cleared so that the oscillations produced in the circuit decayed in an entirely normal manner as though not influenced by the breaker, and by the same token, the circuit breaker itself had to absorb no losses.

The data taken at the Philo tests showed substantially 2 to 1 variation in arc length with recovery voltage variation of 10 to 1. That is, although the variation in arc length is not proportional to the recovery rate, there is a pronounced variation in arc length with recovery rate.

In the tests on the Northern States Power System conducted in 1925 and reported by Messrs. Park and Skeats in Philadelphia, October, 1930,[2] a change in arc length of 4 to 1 with recovery rate was noted. One circuit breaker cleared the low recovery rate current and held over the end of its stroke and failed to clear the high recovery rate. The proper conclusion would seem to be therefore, that some minimum recovery rate requirements should be established as part of circuit breaker standards. These minimum requirements would guarantee the users against fair weather circuit breakers, that is, circuit breakers that can be depended upon to do their work only under easy conditions and which fail as soon as they are called upon to perform in serious emergency service. The recovery rate employed should be that provided by the attached circuit. Such a value is determinable by calculation and is not altered by indeterminate vagaries of the attached circuit breaker. It would seem a pity if the oldest known form of oil circuit breaker should be allowed to defeat such an advance in standardization merely by virtue of its own eccentricities. It is felt that positive modern types of oil circuit breakers will provide consistent records of operation. In any case, it should be possible to standardize minimum circuit recovery rates, the handling of which a purchaser is entitled to expect in the circuit breaker which he buys.

**H. P. St. Clair:** The subject of rate of rise of recovery voltage and its effect on circuit breaker performance is one of great interest and importance at the present time, and it is very gratifying to find that manufacturers are devoting their research facilities to further intensive investigations such as that described by the authors. This paper provides another definite contribution to our total knowledge of the subject, as it has been demonstrated for the first time that the recovery voltage rate may be affected by the circuit breaker itself. This affords a new and important angle to the entire subject and we are glad that the investigation is to continue with the prospect of obtaining further data along the same lines.

To some of us, however, particularly in connection with the Association of Edison Illuminating Companies committee now engaged in the study of oil circuit breaker testing it is disappointing to note the authors' conclusion to the effect that in view of this demonstration, we must abandon all immediate efforts toward working out even tentative specifications or practices as regards the rates of rise of recovery voltage to be used in testing breakers. Furthermore, we are not so sure that such a conclusion is justified. While the authors have shown that there may be a variation as great as 12 to 1 in the observed rate of rise of recovery voltage under the same circuit conditions, depending upon the type of breaker used, at the same time it is apparent also, and so stated in the paper that a breaker that appreciably reduces the rate of rise of recovery voltage is one with a weak deionizing action and is operating close to the border line of its ability to interrupt the circuit.

It seems to us therefore that in the case of modern breakers using efficient arc-extinguishing devices and principles, the rate of rise of recovery voltage on any given circuit will not vary greatly and will not be appreciably reduced. In fact, it seems to be true that a reduction in the recovery rate caused by the breaker itself should be considered a definite indication of incompetent performance on the part of the breaker. On this basis we firmly believe that tentative specifications or practices should be worked out, covering minimum values of recovery rates to be used in designing and testing breakers.

To this end it is to be hoped that other manufacturers will conduct similar investigations to determine the performance of their particular designs as regards the possible reduction of rate of rise of recovery voltage by the breaker itself.

**J. Slepian:** The application of the cathode ray oscillograph by the authors to the study of a-c arcs in oil circuit breakers has led to interesting and important results, as the conclusions given in the paper well show. They bring to us most forcibly that the picture we have been using in describing the extinction of an a-c arc at current zero has been over-simplified. In this picture we assumed that the arc space prior to current zero was of the nature of a conductor with relatively low resistance and that subsequent to current zero it was of the nature of an insulator with a negligible leakage and with a dielectric strength growing rapidly from a very low value at the moment of current zero to a value surpassing that of the circuit voltage if the arc was not reignited. This simple picture was useful. It brought attention to the important part played by the transient characteristic of the circuit in the extinction process, although it led also to the erroneous conclusion that the transient did not begin until the current zero, and that the transient ran its course determined entirely by external circuit constants unless the arc was reignited in which case it ran its own independent course until the dielectric space broke down. But the oscillogram of Fig. 6 shows that in a circuit having considerable electrostatic capacity the arc space may become a fairly good dielectric even before the zero of the main current, and the oscillogram of Fig. 7 shows that the arc space after current zero may be a sufficiently good conductor to greatly modify the transient characteristic of the circuit.

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[1] *Circuit Breaker Field Tests*, A.I.E.E. Trans., June 1931, p. 513.

[2] *Circuit Breaker Recovery Voltages*, A.I.E.E. Trans., March 1931, p. 204.

Abandon the simple picture, and we may say that the arc space changes not from conductor to insulator with growing dielectric strength, precisely at current zero, but that it changes in a continuous manner from conductor to very leaky insulator with low dielectric strength, to less leaky insulator with higher dielectric strength and so on until the state of good insulator is reached. The dielectric strength will begin to develop before the current zero, although usually the leakage will be great enough to carry the diminishing current without overstressing the space. The discontinuity in the nature of the arc space at current zero, required by the simple theory and which we should have recognized as a weakness, is now eliminated.

Other evidence that the arc space possesses dielectric strength before current zero is given in the writer's paper in *Electrotechnik und Maschinenbau* of April 1933. This dielectric strength must not be confused with the arc voltage. Where the current is decreasing, however, as at the end of one-half cycle, we may be sure that the dielectric strength is greater than the momentary arc voltage. Hence, in Fig. 3, we may be sure that even prior to the current zero the arc space had a dielectric strength greater than 15,000 volts, a surprisingly large figure in the light of the simple theory. Similarly the leakage of 30 amperes subsequent to current zero as shown in Fig. 9 is surprisingly large.

The almost complete suppression of the current in the arc prior to the zero of the main current for a capacitative circuit as shown in Fig. 6 reminds one of the "arc failure" prior to current zero discovered by Attwood, Dow and Krausnick[3] in their research with the cathode ray oscillograph on the short a-c arc with copper electrodes in air. However, it seems quite certain that the two phenomena are quite different in their nature. Messrs. Dow, Attwood, and Timoshenko in their paper (see page 926 of this issue) show quite conclusively that their arc failure is due to the sudden substitution of a glow cathode for an arc cathode prior to current zero. But at high pressures a glow cathode can account for only a few hundred volts, whereas the voltage which Van Sickle and Berkey observe starts at 5 kilovolts and rises to 20 kilovolts. The writer suggests as explanation the rupturing of the last current carrying filament by the turbulent gas blast. The electrostatic capacity of the circuit permits the ends of the broken filament to separate far enough to bear the growing voltage.

The application of the cathode ray oscillograph to a-c arc extinction phenomena by the authors has certainly proved its great value, and it is to be hoped that they and others will continue this study for other types of breakers and ranges of power.

**W. F. Skeats:** While it has been appreciated for some time that a deviation from what was considered ideal circuit breaker behavior prior to current zero would produce some changes in the magnitude of the recovery voltage oscillations, the authors have made a new contribution in showing that sufficient current may be passed by the breaker after the "final" current zero to modify appreciably the recovery characteristic of the circuit.

It seems reasonable that this phenomenon should be more noticeable in plain-break breakers with their long arc lengths and relatively unconfined arc cross-sections than in the more modern breakers with their shorter arc lengths and restricted sections, as the greater volume of conducting material allows a greater absorption of energy without breakdown. As will be shown, the records which we have on oil-blast circuit breakers confirm this hypothesis, and the same is true of the data presented by the authors.

Interesting cathode ray oscillograms were obtained in connection with oil circuit breaker tests made at the Richmond plant of the Philadelphia Electric Company on February 26, 1933. Oscillating frequencies of about 200,000 cycles were anticipated, and it was desired to spread each oscillation out over at least one-tenth of an inch. This involved a film or sweep speed of about 1,700 ft per second which is out of the question for a revolving drum. At the same time, it was particularly desired to obtain a record of the early part of the voltage recovery, so that tripping on recovery voltage itself did not seem attractive.

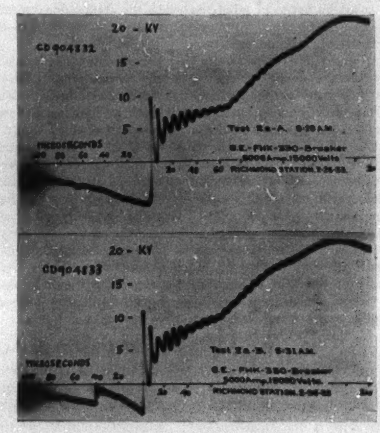

Fig. 1—Recovery Voltage Characteristics with Reactor Located Close to Breaker

The scheme used accomplished the timing in 2 steps. The first step took advantage of the extreme uniformity in the performance of the oil-blast circuit breaker as regards arc length. An auxiliary contact operated from the operating rod of the breaker was set to close the contacts of a high speed relay during the last expected half cycle of current flow. Although a few years ago this procedure would have been quite absurd, the oil-blast breaker was so consistent in its performance that the correct half cycle was selected on 8 of 9 CO tests.

But it was not sufficient merely to select the correct half cycle; a second step was required, giving notice within a fraction of a millisecond when the current zero was about to occur. This function was performed by a special current transformer with a secondary winding open-circuited. A voltage surge appeared across the secondary terminals on this transformer, starting at the desired length of time before the current zero, and this surge was used to trip the cathode ray oscillograph.

Two of the oscillograms obtained are shown in Fig. 1. These were obtained on a circuit in which a current limiting reactor was placed close to the breaker and a powerful circuit connected behind the reactor. This type of circuit results in a comparatively high amplitude oscillation at high frequency. In this case, 2 frequencies were observed, at approximately 190,000 cycles and 160,000 cycles, resulting in a beat phenomenon. Superimposed on these oscillations is a logarithmic curve arising from the circuit behind the reactors, which consisted of generators at the local station and a few miles of cable from a neighboring station. Reflections from the far end of the cable also are plainly discernible.

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[3] A.I.E.E. Trans., v. 50, 1931, p. 584.

These oscillograms offer an excellent basis for the detection of any current flow after the apparent current zero. Recovery voltage is applied very rapidly so as to make the most of any conduction that does occur. Furthermore, due to the low value of capacitance involved in the high frequency oscillation, the energy involved also is low, and hence a small loss can readily be detected. A careful analysis of these oscillograms indicates a 3 per cent reduction in recovery rate in the case of the lower record and a 20 per cent reduction in the case of the upper record. A comparison of the 2 figures indicates that what loss occurs takes place before the voltage crosses the zero axis and thus does not constitute conduction in the reverse direction.

It must be borne in mind that with the tremendous possible range of variation in recovery rates, a reduction of 20 per cent is comparatively insignificant.

The writer finds it necessary to disagree directly with one of the authors' conclusions: that it is futile at the present time to specify recovery rates in connection with circuit breaker tests. The fact still remains that there is such a thing as a system characteristic that may be defined as the curve which would be obtained with an ideal breaker and which has a definite bearing on circuit breaker performance. Moreover, if the performances of 2 or more breakers are to be compared, it should be on the basis of the system characteristic rather than the recovery voltage curves actually obtained. Thus the only deterrent which the authors have brought forward is the fact that this characteristic cannot always be measured in the process of testing. This is unfortunate, but hardly of sufficient importance to warrant taking no recognition of recovery phenomena, particularly as, in the case of modern breakers, the difficulties tend to become negligible or disappear altogether.

**R. C. Van Sickle:** In order to eliminate incorrect and unfair comparisons of test results, and to assure customers that they are obtaining adequate breakers, a minimum standard for circuit breaker testing circuits would be desirable. However, if such standards are to be useful and lasting, they must be based on a careful consideration of all factors involved. It was for that purpose that this paper pointed out the significance of the various types of transients that appear in laboratory testing. By comparing cathode ray oscillograms of test interruptions with the typical oscillograms presented in this paper, it is possible to judge the performance of the breaker and to state that the breaker is operating safely, or that it is struggling to extinguish the arc.

A standard based on the natural frequency of the circuit would eliminate the effect of the breaker. This frequency, if calculated, is subject to errors, particularly for the higher values for which the magnitudes of inductance and capacity are small, and the waves become complicated when 2 or more frequencies are superimposed. Hence calculated values should be checked by actual measurements with cathode ray oscillograms; but in some cases these measured values may be determined partly by breaker performance.

Mr. Prince referred to oscillograms on a 132-kv circuit and the 7.6-kv single-phase oscillograms presented in this paper, to compare them with respect to relative arc voltages and types of transients. Since the ratio of arc voltage to restored voltage varies with restored voltage, being higher for low voltages, better comparisons can be made if the voltages are similar.

The 132-kv oscillograms can be compared with the 132-kv single phase test reproduced as Fig. 3 of a paper by Van Sickle and Leeds presented in 1932[4], or with Fig. 6 of the present paper, a 44-kv single-phase test. In both of these oscillograms the arc voltages are very low; and since the negative peaks of arc voltage are on the envelope of the transient oscillations, no currents flowed through the breakers to modify the phenomena.

The three 7,600-volt oscillograms can be compared with the oscillograms shown by Mr. Skeats. At these lower voltages, high deionizing activity apparently produces relatively high peaks of arc voltage.

However, we are not sure that even breakers equipped with modern circuit interrupting devices always extinguish the arc without permitting some leakage current and producing some modification of the transient. For instance on the oscillograms shown by Mr. Prince it is possible to draw an envelope of the transient oscillations of the 600 volts per microsecond test so that the envelope includes the negative peak of voltage. Evidently no leakage current flowed. However, for the test at 2,400 volts per microsecond we are by no means sure that an envelope can be drawn to include this negative peak of voltage.

More data at various voltages and currents are needed for each type of interrupter before general conclusions can be drawn, and we believe that these data should be available before standards are adopted.

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[4] A.I.E.E. Trans., March 1932, p. 177.

# Classification of Bridge Methods of Measuring Impedances

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***Synopsis.**—An analysis is made of the requirements for satisfactory operation of the simple four-arm bridge when used for impedance measurements. The various forms of bridge are classified into two major types called the ratio-arm type and the product-arm type, based on the location of the fixed impedance arms in the bridge. These two types were subdivided further, based on the phase relation which exists between the fixed arm impedances. Eight practical forms of bridges are given, three of them being duplicate forms from the standpoint of the method of measuring impedance. These bridges together allow the measurement of any type of impedance in terms of practically any type of adjustable standard. The use of partial substitution methods and of resonance methods with these bridges is discussed and several methods of operation are described which show their flexibility in the measurement of impedance.*

* * * * *

## INTRODUCTION

BRIDGE methods have been used for the measurement of impedance from the very beginning of alternating current use. In fact, the history of the impedance bridge dates back to the earlier bridges developed for the measurement of direct current resistance. While some objection may be raised to this method of measurement on the count that it is not direct indicating, in the sense that an ammeter or voltmeter is, this has been more than offset by the high accuracy of which it is capable. Bridge methods of measuring impedance have continued accordingly to hold a high place in the field of electrical measurements and except perhaps at the higher radio frequencies are considered supreme for this purpose over the whole frequency range, where high accuracy is the principal requirement.

The peculiar advantages of the bridge method are most evident where emphasis is laid on the circuit characteristics rather than on power requirements. In power engineering it may be more logical to make measurements in terms of current, voltage, and power, since these are the quantities of immediate interest. In communication engineering, however, where design is based for the most part on circuit characteristics, and power considerations are only of secondary interest, it is natural that bridge methods, which furnish a direct comparison of these circuit characteristics should generally be preferred.

Due to the wide field of usefulness and great flexibility of the impedance bridge, a very large amount of development work has been done and a considerable amount of literature has been published covering various types and modifications. In fact, the subject has become so broad and the information so voluminous that the engineer who has not specialized in the subject has every excuse for a feeling of considerable confusion when he finds it necessary to make a choice among the numerous circuits available. Perhaps the greatest single obstacle to a still more extensive use of the impedance bridge in industry is this very multiplicity of types combined with a rather complete lack of any practical guide for the engineer who is interested principally in the measurement itself and looks on the bridge simply as a means to this end.

Very little information is available as to the relative merits of the various types of bridges, the great majority of published articles being confined to a description of a particular circuit used by the author for a particular purpose.

The present article furnishes a comparison of the relative merits of the large number of circuits which are available for making the same measurement and should serve as a guide to the engineer who is more interested in results than in acquiring a broad education in bridge measurements. An outline is given of the fundamental requirements which must be met by bridges used for impedance measurements, and a classification is made which serves as a help in the choice of a bridge for any particular type of measurement. The relative merits of the simpler types of bridge are discussed from the standpoint of the measurement of both components of an impedance, particularly with reference to measurements in the communication range of frequencies from about 100 to 1,000,000 cycles. Where only the major component of an impedance is desired, for instance where only the inductance of a coil or the capacitance of a condenser is desired, the requirements are not so severe and many forms of bridges may be used which are not suitable for the purpose here outlined. Bridges are also used to a large extent for other purposes than impedance measurements, such as for frequency measurements. These applications will not be considered here.

## THE GENERAL BRIDGE NETWORK

Any bridge may be considered as a network consisting of a number of impedances which may be so adjusted that when a potential difference is applied at two junction points, the potential across two other junction points will be zero. For this condition, there are relations between certain of the impedances which enable us to evaluate one of them in terms of the others. Thus the bridge is essentially a method of comparing impedances. The impedances of the bridge may consist of resistance, capacitance, self- and mutual-inductance, in any combinations, and they may actually form a much more complicated network than the simple circuit shown in Fig. 1. Consequently, the number of different bridges which can be devised for the measurement of impedances is extremely large. However, since only 4 junction points are significant, any bridge circuit may be reduced to a network of 6 impedances connected between these 4 points, as shown in Fig. 1. These impedances are direct impedances, that is, there are no mutual impedances between them.

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If a potential is applied at *BD* and the balance condition is that the potential be zero across *AC*, then the points *BD* are called the input or power source terminals and the points *AC* are called the output or detector terminals. The impedances $Z_{BD}$ and $Z_{AC}$ then act simply as shunts across the power source and detector respectively and do not affect the balance relation. The balance is not affected if the power source and detector are interchanged in a bridge reduced to this simple form and hereafter no distinction will be made in this respect.

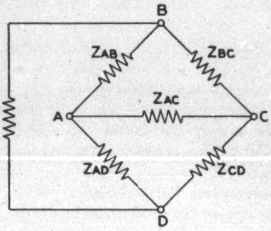

Fig. 1—Schematic of the Impedance Bridge Reduced to its Simplest Form

After the bridge has been reduced to the form of Fig. 1, the equation for balance is

$$Z_{CD} Z_{AB} = Z_{BC} Z_{AD}$$

from which

$$Z_{CD} = \frac{Z_{BC} Z_{AD}}{Z_{AB}} \tag{1}$$

Thus, if $Z_{CD}$ is the unknown impedance, equation (**1**) evaluates it in terms of the other three impedances. Equation (**1**) is a vector equation and therefore the value of $Z_{CD}$ both in magnitude and phase, or both components of it when considered as a complex quantity, may be obtained from this equation.

Although the above equations and subsequent discussion are based primarily on the use of impedances, it should be remembered that all of these relations may be obtained in the same general form if the bridge arms are considered as admittances.

## THE BRIDGE REQUIREMENTS

If the impedances of equation (**1**) are replaced by the complex equivalents $R + jX$, then

$$R_{CD} + jX_{CD} = \frac{(R_{BC} + jX_{BC})\,(R_{AD} + jX_{AD})}{R_{AB} + jX_{AB}} \tag{2}$$

From this equation $R_{CD}$ and $X_{CD}$ may be evaluated in terms of the other 6 quantities. Thus, if each component of the impedances of 3 arms is known, each component of the fourth impedance in terms of the other 6 components can be determined.

In obtaining the balance, any or all of the 6 component impedances occurring in the right hand side of equation (**2**) may be adjusted. Since there are two unknown quantities to be determined, at least two of these components must be adjusted. From the standpoint of simplicity and speed in operation and in order to keep the cost of the circuit to a minimum, it is desirable that not more than two of the known components be adjustable. It is also essential that the choice be such that a variation of one adjustable standard balance one component of the unknown, irrespective of the other component. In other words $R_{CD}$ should be balanced by one known standard, this value of the standard being independent of the magnitude of $X_{CD}$, and, in turn, $X_{CD}$ should be balanced by another standard, the value of which should be independent of the magnitude of $R_{CD}$. This condition of independent adjustment for the two components is essential for satisfactory operation of the bridge, since it allows the balance to be made more rapidly and systematically, and a given setting of one standard always corresponds to the same value of one component of the unknown, independent of the magnitude of the other component, thus allowing the calibration of each of the adjustable standards in terms of the unknown component which it measures.

To meet this requirement, the two components for use as adjustable standards should be so chosen that, when equation (**2**) is reduced to the general form

$$R_{CD} + jX_{CD} = A + jB \tag{3}$$

where *A* and *B* are real quantities, one of the adjustable impedances will appear in *A* and not in *B*, while the other will appear in *B* but not in *A*.

Consideration of equation (**2**) shows that if adjustable standards consisting either of both components of $Z_{BC}$ or of both components of $Z_{AD}$, are chosen, and if the impedances of the two remaining arms are selected so that their ratio is either real or imaginary, but not complex, then equation (**2**) reduces to the form of equation (**3**). No other combination will meet the requirement taking equation (**2**) as it stands. Since for the general case there is no essential difference in the resulting type of bridge whether $Z_{AD}$ or $Z_{BC}$ is used as our adjustable standard, this means that there is really only one method of adjustment, namely the use of both components of one adjacent impedance.

However, if it is realized that parallel components may be used instead of series components for the standard, then equation (**2**) may be rewritten as follows:

$$R_{CD}+jX_{CD}=(R_{AD}+jX_{AD})(R_{BC}+jX_{BC})(G_{AB}-jB_{AB}) \quad \textbf{(4)}$$

where

$$G_{AB}-jB_{AB}=Y_{AB}=\frac{1}{Z_{AB}}$$

From this it follows that $G_{AB}$ and $B_{AB}$ may be used as the adjustable standards, by making the product $Z_{AD}\,Z_{BC}$ real or imaginary.

Thus there are two methods of adjustment possible, either the two series components of an adjacent arm or the two parallel components of the opposite arm.

Having chosen the adjustable standards, there remain in each case two arms, adjacent in one case and opposite in the other, which have fixed values. These impedances must meet certain definite requirements, as already stated.

For the case of adjustment by an adjacent arm, that is, by $Z_{AD}$, equation (**2**) may be written in the form

$$R_{CD}+jX_{CD}=\frac{Z_{BC}}{Z_{AB}}\,(R_{AD}+jX_{AD}) \quad \textbf{(5)}$$

Then in order that this equation fulfill the requirements expressed by equation (**3**), the vector ratio of the fixed arms must either be real or imaginary but not complex, that is, the difference between their phase angles must be 0 deg, 180 deg or ± 90 deg.

For the case of adjustment by the opposite arm $Z_{AB}$, equation (**4**) may be written in the form

$$R_{CD}+jX_{CD}=Z_{BC}\,Z_{AD}\,(G_{AB}-jB_{AB}) \quad \textbf{(6)}$$

Then in order that this equation fulfill the requirements of equation (**3**), the vector product of the fixed arms must either be real or imaginary, but not complex, that is, the sum of their phase angles must be 0 deg, 180 deg, or ± 90 deg.

In the case of bridges of the type indicated by equation (**5**), the fixed arms always enter the balance equation as a ratio, and therefore are called ratio arms, the bridges of this type being called ratio arm bridges. In the case of bridges of the type indicated by equation (**6**), the fixed arms always enter the balance equation as a product, and therefore are called product arms, the bridges of this type being called product arm bridges.

These two types may be further sub-divided according to whether the term involving the fixed arms is real or imaginary.

It should be pointed out at this time that the fixed arms are fixed in value only to the extent that they are not varied during the course of a measurement. They may be functions of frequency, and may arbitrarily be adjustable to vary the range of the bridge, but they are not adjusted in the course of balancing the bridge.

## CLASSIFICATION OF BRIDGE TYPES

The foregoing discussion shows that all simple four arm bridges meeting the requirements specified may be divided into four types. The balance equations of these four types may now simply be derived from the general equations (**2**) and (**4**).

### *1. Ratio Arm Type—Ratio Real*

If $Z_{BC}/Z_{AB}$ is real,

Then

$$\theta=\theta_{BC}-\theta_{AB}=0° \text{ or } 180°$$

That is

$$Z_{BC}/Z_{AB}=R_{BC}/R_{AB}=X_{BC}/X_{AB} \quad \textbf{(7)}$$

Substituting equation (**7**) in equation (**5**) and separating

$$R_{CD}=\frac{R_{AD}R_{BC}}{R_{AB}}=\frac{R_{AD}X_{BC}}{X_{AB}} \quad \textbf{(8)}$$

and

$$X_{CD}=\frac{X_{AD}R_{BC}}{R_{AB}}=\frac{X_{AD}X_{BC}}{X_{AB}} \quad \textbf{(9)}$$

For this type it follows from equations (**8**) and (**9**) that the components of $Z_{CD}$ are balanced by components of $Z_{AD}$ of the same phase, that is $R_{AD}$ will balance $R_{CD}$, and $X_{AD}$ will balance $X_{CD}$.

### *2. Ratio Arm Type—Ratio Imaginary*

If $Z_{BC}/Z_{AB}$ is imaginary

Then

$$\theta=\theta_{BC}-\theta_{AB}=\pm 90°$$

That is

$$Z_{BC}/Z_{AB}=jX_{BC}/R_{AB}=-jR_{BC}/X_{AB} \quad \textbf{(10)}$$

Substituting equation (**10**) in equation (**5**) and separating

$$R_{CD}=-\frac{X_{AD}X_{BC}}{R_{AB}}=\frac{X_{AD}R_{BC}}{X_{AB}} \quad \textbf{(11)}$$

and

$$X_{CD}=\frac{R_{AD}X_{BC}}{R_{AB}}=-\frac{R_{AD}R_{BC}}{X_{AB}} \quad \textbf{(12)}$$

For this type it follows from equations (**11**) and (**12**) that the components of $Z_{CD}$ are balanced by components of $Z_{AD}$ 90 deg out of phase, that is $X_{AD}$ will balance $R_{CD}$ and $R_{AD}$ will balance $X_{CD}$.

### *3. Product Arm Type—Product Real*

If $(Z_{BC}Z_{AD})$ is real

Then

$$\theta=\theta_{BC}+\theta_{AD}=0° \text{ or } 180°$$

That is

$$Z_{BC}Z_{AD}=Z_{BC}/Y_{AD}=R_{BC}/G_{AD}=-X_{BC}/B_{AD} \quad \textbf{(13)}$$

Substituting equation (**13**) in equation (**6**)

$$R_{CD}=\frac{G_{AB}R_{BC}}{G_{AD}}=-\frac{G_{AB}X_{BC}}{B_{AD}} \quad \textbf{(14)}$$

and

$$X_{CD}=-\frac{B_{AB}R_{BC}}{G_{AD}}=\frac{B_{AB}X_{BC}}{B_{AD}} \quad \textbf{(15)}$$

For this type the components of $Z_{CD}$ are balanced by components of $Y_{AB}$ of the same phase, that is $G_{AB}$ will balance $R_{CD}$ and $B_{AB}$ will balance $X_{CD}$.

*4. Product Arm Type—Product Imaginary*

If $(Z_{BC}Z_{AD})$ is imaginary

Then

$$\theta = \theta_{BC} + \theta_{AD} = \pm 90^\circ$$

That is

$$Z_{BC}Z_{AD} = Z_{BC}/Y_{AD} = jR_{BC}/B_{AD} = jX_{BC}/G_{AD} \qquad (\mathbf{16})$$

Substituting equation (**16**) in equation (**6**)

$$R_{CD} = \frac{B_{AB}R_{BC}}{B_{AD}} = \frac{B_{AB}X_{BC}}{G_{AD}} \qquad (\mathbf{17})$$

and

$$X_{CD} = \frac{G_{AB}R_{BC}}{B_{AD}} = \frac{G_{AB}X_{BC}}{G_{AD}} \qquad (\mathbf{18})$$

For this type the components of $Z_{CD}$ are balanced by components of $Y_{AB}$ 90 deg out of phase, that is $B_{AB}$ will balance $R_{CD}$ and $G_{AB}$ will balance $X_{CD}$.

The relations given in these equations are summarized in Table I.

TABLE I—BRIDGE TYPES

| Unknown | Adjustable standard | | | |
|---|---|---|---|---|
| | Ratio arm type | | Product arm type | |
| | Ratio real | Ratio imaginary | Product real | Product imaginary |
| $R_{CD}$ | $R_{AD}$ | $X_{AD}$ | $G_{AB}$ | $B_{AB}$ |
| $X_{CD}$ | $X_{AD}$ | $R_{AD}$ | $B_{AB}$ | $G_{AB}$ |
| *$G_{CD}$ | $G_{AD}$ | $B_{AD}$ | $R_{AB}$ | $X_{AB}$ |
| *$B_{CD}$ | $B_{AD}$ | $G_{AD}$ | $X_{AB}$ | $R_{AB}$ |

*These values may be derived by using admittances in place of impedances and *vice versa* throughout.

## ACTUAL BRIDGE FORMS

The fixed arms may be made up of simple resistances or reactances or of complex impedances provided they meet their phase requirements. Since the choice of complex impedances has no practical advantages over simple reactances or resistances, the choice of fixed impedances should obviously be made on the basis of the simplest practical type. So they will be limited for the present to simple resistance, capacitance, and self-inductance.

Fig. 2 gives all of the combinations of fixed arms which meet the phase angle requirements already stated, when limited to simple resistance, inductance, or capacitance. For all forms, the magnitude of one arm is given in terms of the other and of a constant $K$, such that the only term which appears in the balance equation is the term $K$. None of these bridges represents a distinctly new type, but since the classification is by means of the fixed impedance arms, one of them may be used to measure several types of impedance. Accordingly it may correspond to more than one of the well-known bridge types. For this reason, any references to, or comparison with existing special types of bridge are omitted.

TABLE II—BALANCE EQUATIONS

| Unknown | Ratio arm type | | | Product arm type | | |
|---|---|---|---|---|---|---|
| | $\theta = 0$ | $\theta = +90^\circ$ | $\theta = -90^\circ$ | $\theta = 0$ | $\theta = +90^\circ$ | $\theta = -90^\circ$ |
| $R_{CD} =$ | $KR_{AD}$ | $KL_{AD}$ | $K/C_{AD}$ | $KG_{AB}$ | $K/L_{AB}'$ | $KC_{AB}'$ |
| $L_{CD} =$ | $KL_{AD}$ | .. | $KR_{AD}$ | $KC_{AB}'$ | $KG_{AB}$ | .. |
| $C_{CD} =$ | $KC_{AD}$ | $1/KR_{AD}$ | .. | $KL_{AB}'$ | .. | $1/KG_{AB}$ |
| $G_{CD} =$ | $KG_{AD}$ | $1/KL_{AD}'$ | $C_{AD}'/K$ | $R_{AB}/K$ | $L_{AB}/K$ | $1/KC_{AB}$ |
| $L_{CD}' =$ | $KL_{AD}'$ | .. | $K/G_{AD}$ | $C_{AB}/K$ | $K/R_{AB}$ | .. |
| $C_{CD}' =$ | $KC_{AD}'$ | $G_{AD}/K$ | .. | $L_{AB}/K$ | .. | $R_{AB}/K$ |
| Figures | 2*A*<br>2*B*<br>2*C* | 2*D*<br>2*F**  | 2*E*<br>2*G** | 2*H*<br>2*I* | 2*J** | 2*K* |

$R$, $L$ and $C$ = series components of complex arms.
$G$, $L$, and $C'$ = parallel components of complex arms.
$K$ has the value indicated on the individual circuits of Fig 2.
$\theta = \theta_{AB} - \theta_{BC}$ for ratio arm type
$\theta = \theta_{AD} + \theta_{BC}$ for product arm type

*These forms are not practical.

Table II gives the balance equations for each type of bridge for the measurement of any component of the unknown impedance in terms of resistance, capacitance, and inductance. These equations simply are derived from the general equations (**8**) to (**18**) by substitution of circuit constants for impedances and by the introduction of the constant $K$. This constant must be evaluated from the relation between the ratio arms or product arms shown in the individual bridge forms of Fig. 2. At the bottom of Table II are given the corresponding bridge figures for reference. This table shows no bridges having a phase relation of 180 deg between the fixed arms. A little consideration will show that

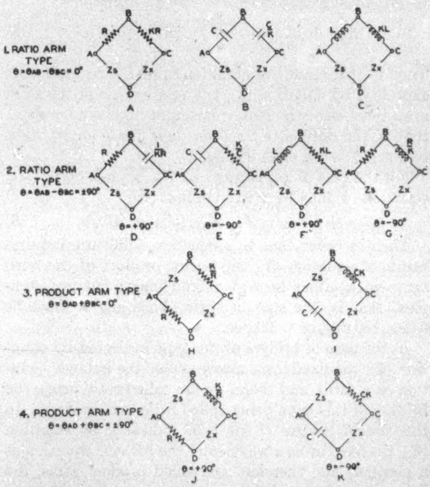

Fig. 2—The Various Forms of 4-Arm Bridges Divided Into Four Types

since the phase relation between the unknown and the standard for such bridges must also be 180 deg, they cannot be used to measure any but pure reactances or negative resistances. Accordingly, they are not considered herein. In the case of the 90 deg relation, both signs must be considered and result in bridges that are complementary with respect to one another, that is while one measures only inductive impedances, the other measures only capacitive impedances. Thus Table II shows the imaginary type subdivided into two sub-types, depending on the sign of the angle.

As an example of the use of this table: Suppose it is desired to measure the series resistance and inductance of an unknown impedance. This may be done by using adjustable standards of series resistance and inductance, series resistance and capacitance, parallel resistance and capacitance, or parallel resistance and inductance, by choosing the particular type of bridge for the purpose. For instance, referring to Table II, if it is desired to measure the series resistance in terms of conductance, and the series inductance in terms of parallel capacitance, the product arm bridge with real ratio, that is, either Fig. 2*H* or 2*I*, would be used.

Since there are 6 types of balance equations given in Table II, it follows that 5 of the circuits of Fig. 2 are duplicates of others from the standpoint of the balance equations which they give. For instance, there is no difference whatever in the theoretical operation of the bridges of Figs. 2*A*, 2*B*, and 2*C*. The choice must be determined entirely from other considerations. In the same way, as indicated by the figures tabulated in Table II, Figs. 2*D* and 2*F* give identical results as do Figs. 2*E* and 2*G*, and Figs. 2*H* and 2*I*. From the practical standpoint, there may be, and actually there is, considerable difference in the merits of these different forms. At this time, we may simply state that where a choice is possible, resistance is the preferred form of fixed arm and capacitance is preferred to inductance. This allows us to choose our preferred forms as Fig. 2*A*, Fig. 2*D*, Fig. 2*E*, and Fig. 2*H*.

A study of Table II shows that bridges of fixed ratio arm type always measure the series components of the unknown in terms of series components of the standard and, conversely, they measure the parallel components in terms of parallel components of the standard. Bridges of product arm type measure the series component of the unknown in terms of parallel components of the standard and conversely.

None of the balance equations of Table II includes frequency, that is, all of them allow the evaluation of each component of the unknown directly in terms of a corresponding component of the standard with the exception that in some cases the relation is a reciprocal one. Practically any form of standard maybe chosen in order to measure a given type of unknown impedance.

## PRACTICAL CONSIDERATIONS

So far the question whether the requirements for the fixed arm impedances given in Fig. 2 can be met in practise has not been considered. It may be well to point out that the performance of the bridge is determined very much by the degree to which the phase angle requirements are met. If there is appreciable error here, the two balances will not entirely be independent and necessary corrections will be complicated and difficult to make. Consequently, the first essential for a satisfactory bridge is that its fixed arms meet their phase angle requirements. For a general purpose bridge these requirements must hold independent of frequency at least over an appreciable frequency range.

The forms given in Fig. 2 meet their phase angle requirements at all frequencies provided the arms actually are pure resistances or reactances. If they have residuals associated with them, it is still possible to meet the phase angle requirements in most cases, at least over a reasonable frequency range, as discussed below.

Resistances can be made to have practically zero phase angle and condensers, particularly air condensers, may be made to have phase angles of practically 90 deg. In the case of condensers having dielectric loss, this loss may be kept quite small. However, it takes such a form that the phase difference of the condenser approximately is independent of frequency. For this reason, it can not be represented accurately either as a fixed resistance in series with the condenser or as a fixed conductance in shunt, when considered over a frequency range. Due to the small amount of this loss, it usually is satisfactory to represent it in either one form or the other, whichever is the more convenient.

In the case of inductance, there is always a quite appreciable series resistance which, for the usual size of coil, can not be neglected and must accordingly be corrected for.

With the above considerations in mind, the forms of Fig. 2 may now be reconsidered from the practical standpoint. It is readily seen that the requirements of the real ratio type bridge can be met using resistances, capacitances, or inductances. In the case of the imaginary ratio type, the requirements can be met, at least very approximately, in the case of Figs. 2*D* and 2*E*. However, in the case of Figs. 2*F* and 2*G*, any resistance in series with the inductance must be corrected by a capacitance in series with the resistance, if the correction is to be independent of frequency. Since the value of this series capacitance will, in general, be large, this form of correction is unsatisfactory. For instance, for a bridge in which the value of $R$ is 1,000 ohms and the inductance has a high time constant, the series capacitance required is in the order of $3\mu$f. By using a standard of inductance having larger series resistance, we may reduce this capacitance, but we then have a form of bridge which is, in effect, a compromise between Figs. 2*F* and 2*G*, and Figs. 2*D* and 2*E*, which has no practical advantages over the latter. Accordingly, the forms of Figs. 2*F* and 2*G* must be considered impractical, particularly as Figs. 2*D* and 2*E* give identical performance.

In the case of the product arm type the requirements can be met by Fig. 2*H* and can be met by Fig. 2*I* by adding a conductance in shunt with the capacitance to compensate for the series resistance of the inductance. However, even though this allows us to meet the requirement, this form is less satisfactory than that of Fig. 2*H* due to the difficulty of designing an inductance standard having inductance and series resistance invariable over an appreciable frequency range. Again the requirements can readily be met by Fig. 2*K*, but in the case of Fig. 2*J* series resistance of the inductance can be corrected only by shunting the resistance arm by pure inductance, which is impractical. This is unfortunate since it rules out one form of bridge for which there is no duplicate and, consequently, makes the measurement of inductive impedances by bridges of this type impractical.

Summarizing the above, practical considerations rule out Figs. 2*F*, 2*G*, and 2*J*, reducing to 5 the number of different bridge types. There are 8 forms remaining, namely 3 of the real ratio type, each capable of giving the same performance; 2 of the imaginary ratio type which are complementary, together giving a measurement of inductive and capacitive impedances; one of the real product type which will measure all types of impedance; and one imaginary product type which is capable of measuring only capacitive impedances.

The only duplicate forms are in the case of the real ratio and real product types. In the case of the latter, Fig. 2*H* is to be preferred in practically all cases to Fig. 2*I*, as already explained, and thus we can say that, practically speaking, we have duplicate forms only in the case of the real ratio type.

The three forms of this type are all used and each has certain advantages for certain types of measurements. This type of bridge, commonly known as the direct comparison type, probably is used more than any other, and is one of the most accurate types, particularly in the special case of equal ratio arms. This is due to the fact that a check for equality of the ratio arms may readily be made by a method of simple reversal without any external measurements, and by this means practically all the errors of the bridge may be eliminated. Resistance ratio arms are preferable for a general purpose bridge because they are more readily available and more readily adjusted to meet their requirements. They also give an impedance independent of frequency, which usually is desirable. Capacitance ratio arms have certain advantages for particular cases. They may readily be chosen to give high impedance values, this being an advantage in certain cases, for instance in the measurement of small capacitances at low frequencies. This form also is desirable where high voltages must be used, since the ratio arms may be designed to withstand high voltages without the dissipation of appreciable energy. It also has the advantage that where measurements are desired with a direct current superimposed on the alternating current, the direct current automatically is excluded from the ratio arms and thus all of the direct current applied to the bridge passes through the unknown and there is no dissipation due to the direct current in the ratio arms. The impedance of the ratio arms decreases as the frequency increases, which usually is a disadvantage but may have advantages in some cases, such as the measurement of capacitance. There may be a disadvantage, in some cases, due to the load on the generator being capacitive, thus tending to increase the magnitude of the harmonics, and again, in the case of the measurement of inductances, there may be undesirable resonance effects.

The inductance ratio arm type has advantages where heavy currents must be passed through the bridge, since the ratio arms of this type may be designed to carry large currents with low dissipation. A modification of this type, where there is mutual inductance between the ratio arms, gives the advantage of ratio arms of high impedance with a corresponding low impedance input. A further modification consists in making the ratio arms the secondary of the input transformer, thus combining in one coil the functions of ratio arms and input transformer. This form, of course, departs from the simple four-arm bridge, but is mentioned here due to its simplicity and actual practical advantages.

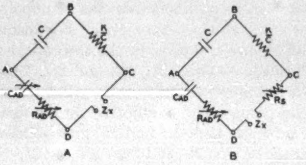

FIG. 3

*A.* BRIDGE OF TYPE 2 FOR MEASURING SELF-INDUCTANCE

*B.* THE SAME BRIDGE MODIFIED BY THE USE OF PARTIAL SUBSTITUTION

## SUBSTITUTION METHODS

In any of the bridges discussed and, in fact, in practically all bridges, it is possible to evaluate the unknown by first obtaining a balance with the unknown in the circuit and then substituting for it adjustable standards which may be adjusted to rebalance the bridge. This is, in general, a very accurate method, eliminating to a large degree the necessity for the bridge to meet its phase angle requirement. However, in the case of complete substitution of standards to balance both components of the unknown, the method has no advantage except accuracy over the bridges of type 1, since standards of the same type as the unknown must be used and, in general, this method lacks the flexibility of bridges of type 1, obtained by their unequal ratio arms. On the other hand, the use of substitution to measure the resistance or conductance component of the unknown has many advantages, the principal one being that it allows the choice of a type of bridge that will give directly the reactance component of the unknown in terms of an adjustable resistance and then by use of the substitution method to balance the resistance or conductance of the unknown by means of a second adjustable resistance, thus obtaining the ideal method of balance, using two adjustable resistances.

For the purpose of illustration, the case of the measurement of an inductive impedance may be taken. In general, the most desirable method would be to balance the reactance by means of series resistance. This can be done by means of the bridges of Figs. 2*E* or 2*G*. Choosing Fig. 2*E* as the preferred form, the bridge normally would take the form of Fig. 3*A*.

For normal operation, $C_{AD}$ and $R_{AD}$ would be the adjustable standards. The series inductance of the unknown would be given directly as $KR_{AD}$, while the series resistance would be given as $\frac{K}{C_{AD}}$. This measurement of the series resistance requires an adjustable capacitance and a computation due to the reciprocal relation. Now suppose a fixed value for $C_{AD}$ were used and an adjustable resistance standard $R_S$ placed in series with $Z_X$, giving the form of Fig. 3*B*, in which $R_{AD}$ and $R_S$ are the adjustable standards. If terminals $Z_X$ are short-circuited, the conditions for balance are $R_S = \frac{K}{C_{AD}}$ and $R_{AD} = 0$. Then the unknown $Z_X$ is inserted and the bridge rebalanced. The inductance of the unknown is given, as for Fig. 3*A*, as $KR_{AD}$, but since $C_{AD}$ is unchanged the total resistance in *CD* is unchanged. Therefore, the series resistance of the unknown will be equal to the change in $R_S$ between the two balances.

This bridge circuit may be recognized as the familiar bridge due to Owen,[1] and it is, theoretically at least, when used as described, an exceedingly desirable bridge for inductance measurements.

It should be pointed out here that since either $C_{AD}$ or $R_S$ may equally well be used to balance $R_X$, it is not necessary to use either one or the other exclusively in any one bridge. The adjustments may be combined so that the capacitance adjustment will take care of large changes and $R_S$ of small changes; that is, $C_{AD}$ may be used for coarse adjustment and $R_S$ for fine adjustment. This compromise is, in general, more satisfactory than either method used alone.

The imaginary product arm type, particularly the form of Fig. 2*K* is also well adapted to modification to enable it to measure capacitance and conductance in terms of two adjustable resistances.

There is a further modification of the substitution method, which is in common use. As already explained, there is little practical advantage in the substitution method for measuring either inductance or capacitance. However, there are occasions where the substitution of capacitance for inductance has advantages. Since the reactance of one is opposite in sign to that of the other, the method might more correctly be termed a compensation method, but in common with other substitution methods it can be made irrespective of the type of bridge. Various modifications of the general method may be used, but they are all classed under the general head of resonance methods.

### RESONANCE METHODS

If it is desired to measure the inductance of any inductive impedance, a capacitance standard may be inserted in series with it, and adjusted until the total reactance of the combination is zero. The only function the bridge performs is to measure the effective resistance of the combination and to determine the condition of zero reactance. Any of the bridges of Fig. 2 will do this satisfactorily, but those of real ratio type that is, the simple comparison type, are the most satisfactory since they give the resistance directly in terms of an adjustable resistance standard. This type of bridge usually is termed a series resonance bridge. The value of the inductance is computed from the resonance formula $\omega^2 LC = 1$. It has the disadvantage that it involves the frequency, but it has the compensating advantage that the method, being essentially a direct measurement of the resistance of the resonant circuit, is very accurate for the measurement of effective resistance.

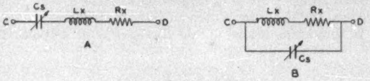

FIG. 4

*A*. THE *CD* ARM OF THE BRIDGE AS USED FOR SERIES RESONANCE MEASUREMENTS

*B*. THE *CD* ARM OF THE BRIDGE AS USED FOR PARALLEL RESONANCE MEASUREMENTS

The condenser may equally well be shunted across the unknown, in which case the bridge circuit is called a parallel resonance bridge. However, if the ratio of reactance to resistance of the unknown is not high, the expression for the series inductance in this case is not as simple as that for series resonance, and is not independent of the value of the effective resistance, that is, the two adjustments are not independent.

Fig. 4 shows the forms taken by the *CD* arm for resonance measurements. Fig. 4*A* is the series resonant circuit using an adjustable capacitance standard. Fig. 4*B* is the parallel circuit using an adjustable capacitance standard.

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[1] D. Owen, *Proc. Phys. Soc. London*, October, 1914.

## Discussion

**W. B. Kouwenhoven:** This paper presents a rather novel grouping of impedance bridges. In addition to the impedance balance relation, equation (1) of the paper, there exists the phase angle balance relation which is

$$\theta_{ab} + \theta_{cd} = \theta_{ad} + \theta_{bc}$$

This relation is very useful in many cases where the power factor of a dielectric is in question.

In any a-c bridge measurement, there are many factors that have to be considered. Among these are: the size and character of the specimen; the constants desired; the frequency range; the required accuracy; the bridge sensitivity; the inherent bridge errors; the question of shielding; the power source; and others. In some cases these factors lead one to choose a parallel arm type of bridge such as the Schering bridge for the work. This class of bridge is not discussed in any detail by the author.

Although impedance bridges usually may be operated as direct reading, the use of a substitution method often simplifies the work and reduces the errors that may be present. There are three classes of substitution methods:

1. In which the bridge is first balanced with the unknown in circuit and then substituting for the unknown an impedance whose constants are accurately known. The bridge is now balanced by adjusting the known impedance. This method requires that the known impedance have the same constants as the unknown.
2. In which the bridge is first balanced with a known variable impedance in the $X$ arm and then the unknown impedance is connected either in series or in parallel with the known variable impedance and the latter is then adjusted for balance.
3. In which the bridge is first balanced with a known fixed impedance in the $X$ arm and then the unknown is connected in that arm and the second balance obtained by adjusting the impedances of one or more of the variable arms of the bridge.

The second method generally is the simplest to use and usually gives satisfactory results.

**John G. Ferguson:** Equation (1) as pointed out in the text is a vector equation and therefore includes the relation between the vector angles mentioned by Professor Kouwenhoven, as well as the relation between their magnitudes.

The equations derived in the paper are based primarily on impedances. However, the relations may be equally well derived in terms of admittances, and Table II gives the equations for each bridge in terms of both parallel and series components. The Schering bridge therefore is fully covered. In fact, Figure 2K represents the Schering bridge in its simplest form if it is assumed that $Z_x$ consists of the unknown imperfect condenser and $Z_s$ consists of a standard condenser in parallel with a standard conductance.

The division of substitution methods into 3 classes is interesting. However, the first 2 classes differ only in degree. In other words, it is immaterial in the general case whether the unknown replaces all of the known standard or only part of it. The third class can be considered a substitution method only in so far as it approaches class 1 or class 2. A true substitution method precludes any change in the variable arms of sufficient magnitude to be recognized as a distinct method of balancing the bridge.

In a theoretical paper such as this, it was not possible to discuss in detail the practical advantages of these bridges but the fact that they are all of the simplest form, having only 4 branch points, and are all at least approximately direct reading, makes it improbable that any more complex type would offer sufficient advantages to justify its preference.

# Better Instrument Springs

## BY ROBERT W. CARSON*

Associate, A.I.E.E.

***Synopsis.****—Electrical measuring instruments play an important part in the generation, distribution, and sale of electrical power, and in the development and testing of electrical machinery. The accuracy of electrical measuring instruments depends as much on the quality of the control springs as on the design of the torque producing elements.*

*Unstable effects found in the application of spiral springs to electrical instruments arise from aging in service and hereditary hysteresis in the spring material. There is little available information in the technical literature on these effects. In order to produce the most satisfactory spring controlled instruments for the electrical industry, there should be recorded in the technical literature a considerable body of detailed information on springs. Information is needed on such subjects as the effect of composition, condition of material, forming methods, stabilizing treatments, design details, residual stresses, service conditions, and temperature on the performance of spiral instrument springs.*

*The information presented in this paper resulted from torsional pendulum tests, hardness tests, spring uncoiling tests, various forming and stabilizing treatments, and measurements of hereditary hysteresis with the grid glow micrometer.*

*The results of these tests are presented graphically, showing that moderate temperature heat treatment has an important effect on hereditary hysteresis, that the softening range of cold worked spring ribbon is very critical, that the forming temperature and forming time have a controlling effect on residual stresses, that a stress relief anneal reduces aging and hereditary hysteresis. The nature of the action of hereditary hysteresis is defined.*

*Additional information is needed on the effect of composition, mechanical condition of the spring material, rolling practise, and the temperature of loading on hereditary hysteresis. Also, the bibliography may not be complete. Discussion on these subjects is invited.*

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ELECTRICAL measuring instruments play an important part in the development and testing of electrical machinery, in the operation and control of electrical equipment, and in the distribution and metering of electrical energy. In these applications of spring controlled instruments, the accuracy depends as much on the performance and stability of the control springs as on the design of the torque producing elements. Such factors as jewels, pivots, permanent magnets, electrical design and the structure of the mechanism are well covered in the technical literature. However, the standard references on instruments, both in this country and abroad, cover only the usual data on the mechanics of spring design, and do not include the knowledge necessary to produce instrument springs of the high quality and performance required in modern sensitive instruments.

There are two unstable effects found in the application of spiral springs to electrical instruments: aging and hereditary hysteresis. Aging is a slow permanent change in the zero position and calibration of the instrument over long periods of time. Hereditary hysteresis is a time lag of the deflection in relation to the applied torque. Hysteresis is a temporary effect evidenced by the failure of the spring to return exactly to the zero position after having been deflected for a long period of time.

There is little data on the effect of aging and hereditary hysteresis on the performance of spiral instrument springs. St. Clair, Rockerfeller, and Brombacher have published some data applying to instrument spring material. However, the literature contains no information that might serve as a guide for determining what constitutes good spring performance, what variables have a controlling influence, and what manufacturing operations produce the most suitable springs. The situation is similar in many respects to the state of the art that existed in the application of permanent magnets before publication of the work of such men as Evershed, Watson, and Mathews. Thus the art of making good permanent magnets was confined to the realms of shop processes, or highly skilled craftsmanship, much of which was based upon experience rather than scientific research. As a matter of fact, excellent magnets were made before Evershed's paper and excellent springs before any publication on the subject. Instrument manufacturers, as is well known, have been making magnets and springs of the highest quality for many years, but unfortunately the fact remains that the literature does not teach the art of making springs.

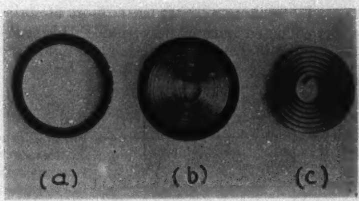

FIG. 1—FORMING INSTRUMENT SPRINGS

(*a*) Forming barrel
(*b*) Barrel filled with spring ribbon ready for forming
(*c*) Formed spiral spring

Information is needed regarding the effect on the performance of spiral springs of such factors as composition, mechanical condition of the spring material, rolling practice, forming methods, stabilizing heat treatments, design details, residual stresses, service conditions, and temperature. It was in recognition of this need that an unpublished paper, *Aging and Elastic Hysteresis in Instrument Springs*, was read before the A.I.E.E. in January, 1932. The present paper includes the data presented in the first report with additional information drawn from the results of several years of practical research on instrument springs and spring materials. While the information in this paper might have been known in equivalent form by certain manufacturers of instrument springs, it certainly has never been published so far as known to the author. Torsional pendulum tests, hardness tests, various forming and stabilizing heat treatments, spiral spring uncoiling tests, and measurements of hereditary hysteresis with the grid glow micrometer were used to obtain this information. An extensive bibliography on the subject of spring defects was collected during the period of this study. A selected list of references from this bibliography is included with this paper.

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*Westinghouse Elec. & Mfg. Co., Newark, N. J.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

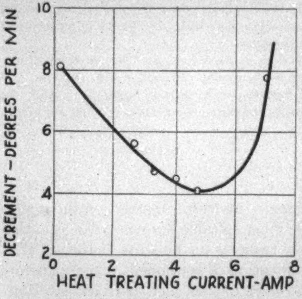


Fig. 2—Effect of Moderate Heat Treatment on the Decrement of Spring Material in the Torsional Pendulum Test

2 per cent tin phosphor bronze wire, 0.010 in dia, 45 per cent cold reduction in area, 100 degree amplitude, max. combined stress —9,000 lb per sq in. 6 amp current caused softening

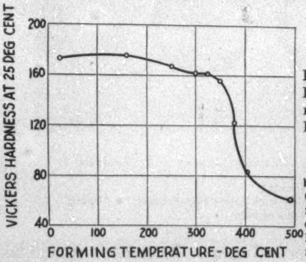


Fig. 3—Effect of Forming Temperature on the Hardness of Spring Ribbon

2 per cent phosphor bronze spring ribbon, 0.015 in. thick, 0.165 in. wide, 85 per cent cold reduction in area Forming time—15 minutes

## Manufacture of Spiral Springs

In the usual shop method of making spiral instrument springs, hard drawn wire of a suitable material such as phosphor bronze is used. The degree of hardness or temper is measured usually by the amount that the cross-section is reduced in cold drawing. This may be expressed by the number of wire sizes or the percent cold reduction in area. For example, an annealed wire 0.064 inch diameter drawn without further annealing to 0.010 inch diameter is 16 numbers hard, or 97.5 percent cold reduction in area.

The hard spring wire is rolled with several passes through the rolls to a hard, thin ribbon. Several lengths of the ribbon are wound together around an arbor, and held tightly wound with a close-fitting barrel as illustrated in Fig. 1. The ribbons in the barrel are then formed to a spiral shape by heating the assembly for several minutes at a moderate temperature, in some instances at 300 deg C. When the ribbons are removed from the barrel they retain an approximation of the spiral shape they assumed when wound in the barrel.

The stresses set up in the ribbons when they are wound into the forming barrel are very high. As the ribbons in the barrel are heated the elastic strength of the material decreases. At the forming temperature the elastic strength is but a small fraction of its room temperature value, and the springs set to the form in which they are constrained in the barrel. However, the high stresses set up in winding the ribbons into the barrel are not completely relieved by the heat treatment, since the material retains some elastic strength at any temperature below the annealing or softening point. Proof of the presence of residual stresses in the ribbon is found in the fact that the springs expand when they are removed from the forming barrel.

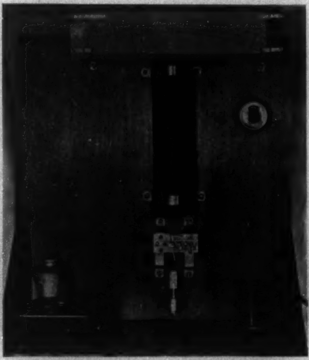


Fig. 4—Oven Used on Softening Tests on Spring Wire

## Effect of Heat Treatment on Hereditary Hysteresis

In the torsional pendulum tests a rotating pendulum was suspended by a 20-inch length of spring wire. The maximum combined fiber stress at an amplitude of 100 deg was approximately 9,000 lb per sq in. with a wire diameter of 0.010 inch. The wire was heat treated under the tension load of the pendulum weight by passing a current through the wire. The decrement of the torsional oscillations was measured after heat treatments at successively higher temperatures. In a typical test a 2 per cent tin phosphor bronze wire with 45 per cent cold reduction in area was used. In this test the decrement or the hereditary hysteresis decreased rapidly as the heat treating temperature approached the softening point, as shown in Fig. 2. In a series of tests using wires of various compositions and varying amounts of cold reduction in area similar results were obtained, with the exception that the effects were greater in wires with more cold working.

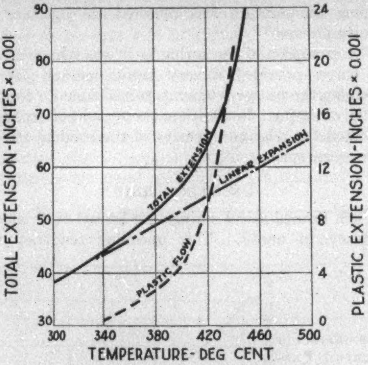


Fig. 5—Softening Test of Spring Wire

2 per cent tin phosphor bronze spring wire, 0.010 in. diam, 12 in. long, 97 per cent cold reduction in area. Tension load—8,000 lb per sq in. Heating rate—35 deg C per minute

## Hardness Tests

Phosphor bronze ribbons with varying amounts of cold reduction in area were subjected to successively higher temperatures, and the effect of this thermal treatment on the hardness of the strips was measured with a Vickers pyramid hardness tester. Large variations in the range of cold reduction in area did not produce corresponding variations in hardness. However, the softening range was found to be very critical as shown in Fig. 3 for a 2 per cent tin phosphor bronze ribbon, 0.015 inch thick and 0.165 inch wide, with 85 per cent cold reduction in area. Heat treating temperatures up to 350 deg C had little effect, but slightly higher temperatures caused a large decrease in hardness. A similar effect was found in all cold worked ribbons, but the initial hardness was not quite as high for lower amounts of cold working.

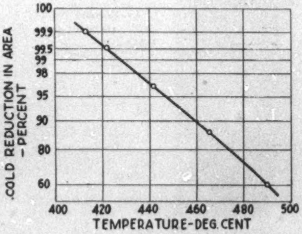
## Softening Tests

One foot lengths of phosphor bronze wire were heated in a small electric oven illustrated in Fig. 4, while under a constant tension load produced by a weight. The wire was clamped at the upper end of the oven and was passed between a pair of small rollers at the lower end. The rollers were held in contact with the wire by light spring pressure. Extension of the part of the specimen inside the oven was indicated by a pointer rotated by one of the rollers. When the wire was heated the pointer indicated the extension caused by thermal expansion. However, at elevated temperatures the tension load introduced permanent creep or plastic extension, in addition to the thermal expansion effect. The test was performed by heating the oven at a uniform rate and measuring the temperature and total extension of the specimen. The plastic extension was obtained graphically by subtracting the calculated temperature expansion from the total extension as shown in Fig. 5 for a typical test. The specimen illustrated was a 2 per cent tin phosphor bronze wire 0.010 inch diameter with 97 per cent cold reduction in area. The tension load was 8,000 lb per sq in. and the heating rate was 35 deg C per minute. In this test there was no plastic extension until a temperature of approximately 330 deg C was reached. As the temperature was further increased the plastic extension increased very rapidly. The occurrence of plastic extension indicated that the material lost strength as the temperature was raised through 330 deg C.

Increased cold working in the spring material was found to lower the temperature at which the loss of strength or plastic extension occurred. The temperature at which the plastic extension reached 0.020 inch was determined for a series of specimens with varying amounts of cold reduction in area. Fig. 6 shows that this temperature fell rapidly as the cold reduction in area was increased. Although this test method is not subject to rigorous interpretation, it demonstrates that the softening temperature of phosphor bronze spring wire is controlled by the amount of cold working in the material.

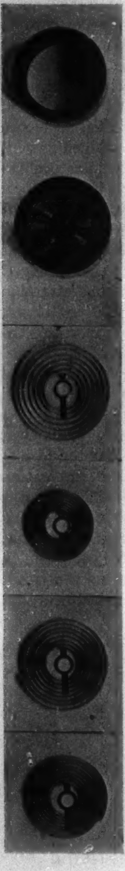
Fig. 6—Effect of Cold Working on the Softening Temperature of Spring Wire

2 per cent tin phosphor bronze spring wire, 0.010 in. dia, 9 in. long tension load —8,000 lb per sq in. heating rate—35 deg C per min. Total plastic extension, 0.020 in.



## Effect of Temperature and Time on the Forming of Spiral Springs

The effect of forming temperature and the time at temperature was investigated using a group of springs made from a spring ribbon prepared for a typical instrument spring. The spring material used was a commercial cold drawn 5 per cent tin phosphor bronze wire 0.008 inch diameter. The ribbon was rolled in 8 passes to a cross-section of 0.0022 by 0.023 inch. The forming barrel, inside diameter 0.436 inch, accommodated 6 lengths of ribbon 9.5 inches long. Barrels filled with spring ribbon were formed at various temperatures from 260 to 320 deg C for 15 minutes. Other barrels were formed at 300 deg C for various lengths of time from 1 to 30 minutes. When the spiral springs were removed from the barrels, the springs expanded so that the outside diameter of the spring was larger than the inside diameter of the forming barrel, as illustrated in Fig. 7. There was less increase in diameter of the spring when the temperature of forming approached the softening point, as shown in the curve, Fig. 8. The time at temperature also affected the amount of expansion. Fig. 9 shows that a minimum time of 20 minutes at the forming temperature was required to complete the forming process.



*A*—Spring forming barrel inside dia—0.436 inch

*B*—Forming barrel wound with six ribbons ready for forming

*C*—Formed at 250 deg C. Outside dia—0.633 in.

*D*—Formed at 320 deg C. Outside dia—0.461 in.

Springs formed in barrel shown in *A*. Heated in air oven for 15 min

*E*—Formed for 4 min. Outside dia—0.578 in.

*F*—Formed for 30 min. Outside dia—0.500 in.

Springs formed in barrel shown in *A*. Heated in air oven at 300 deg C

Fig. 7—Effect of Forming Temperature and Forming Time on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Spring ribbon prepared from commercial 5 per cent tin phosphor bronze spring wire 0.008 in. dia, rolled to ribbon 0.023 in. wide, 0.0022 in. thick. Ribbon length—9.5 in., spring torque—0.27 cm g per revolution

The expansion of the spring as it was removed from the barrel provided a very useful method for determining the proper temperature and time for forming any given spring. In addition, the amount of expansion indicated the relative intensity of the residual stresses in the spiral spring.

## Uncoiling Tests

When formed spiral springs are heated they show a tendency to uncoil. This uncoiling tendency was measured by heating the springs formed for 15 minutes at 300 deg C to various temperatures. Fig. 10 shows that the rate of uncoiling increased very rapidly with only moderate increases in temperature. At 100 deg C the uncoiling rate was nearly 10,000 times as rapid as the rate at 35 deg C. The uncoiling at any constant temperature was found to proceed at a decreasing rate asymptotic to some final value, and the final amount of uncoiling was found to be larger with springs formed at lower temperatures. Measurements of the elastic modulus of the springs (torque per revolution) showed that the uncoiling was accompanied by an increase in the elastic modulus. The effect of forming temperature on the amount of uncoiling and change in elastic modulus is illustrated in Fig. 11. Springs formed at 260 deg C were subject to 3 times as much change as springs formed at 310 deg C. Tests on the springs formed at 300 to 320 deg C disclosed that the small initial uncoiling tendency was removed completely by heating the finished springs for 24 hours at 100 deg C. A small amount of uncoiling took place during this heat treatment, but there was no subsequent uncoiling tendency

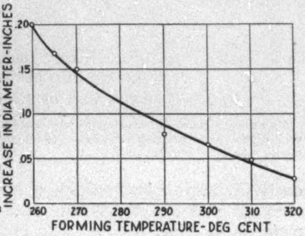


Fig. 8—Effect of Forming Temperature on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Same springs as described in Fig. 7

at any lower temperature. Comparison of Fig. 8 and Fig. 11 shows that the uncoiling tendency, the aging tendency, and the expansion of the spring when removed from the barrel are all influenced in a similar manner by the forming temperature. This fact suggests that residual stresses are responsible for aging and uncoiling effects as well as the expansion effect in spiral springs.

## Grid Glow Micrometer Tests

Hereditary hysteresis effects in spiral springs are very difficult to measure with precision. These effects were investigated using flat strips of spring ribbon loaded in bending as illustrated in Fig. 12. A short length of ribbon was placed on two parallel horizontal pins and loaded with a weight hung midway between the pins. The deflection of the beam was measured with a micrometer head fitted with a sharp contact point. Contact between the micrometer point and the ribbon operated a grid glow tube to indicate the instant of contact. A large diameter drum and a magnifier lens was attached to the micrometer head to facilitate accurate readings, and a constant tension thread drive was used to make accurate settings of the micrometer. An autographic attachment was developed which produced a continuous record of displacements of the test specimen, so that a test could proceed without being disturbed. The grid glow micrometer was found to be sensitive to displacements of 0.00001 inch (ten millionths) with a contact circuit resistance of more than one megohm. With this apparatus precision measurements of hereditary hysteresis in instrument spring ribbon were made at low working stresses and over periods of time extending for several weeks.

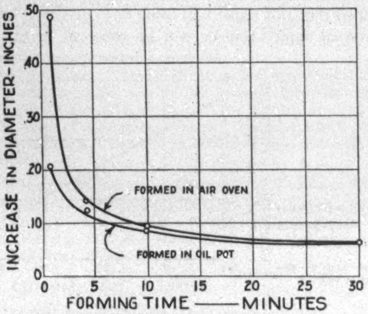


Fig. 9—Effect of Forming Time on the Outside Diameter of Spiral Springs Formed in the Same Barrel

Same springs as described in Fig. 7. Formed at 300 deg C for 15 min

Hereditary hysteresis in instrument spring ribbon was investigated under conditions of load and time similar to the service conditions of the instrument spring. The effect of heat treatment on hereditary hysteresis as obtained from the torsional pendulum test (Fig. 2) was confirmed. The continuous nature of the hysteresis effect is shown in Fig. 13 for a ribbon of 5 per cent nickel bronze, 0.016 by 0.109 inch, with 84 per cent cold reduction in area. The specimen was formed flat at 300 deg C for 15 minutes to relieve cold working stresses. At a maximum stress of 12,000 lb per sq in. the creep reached 0.28 per cent of the load deflection in 30 hours.

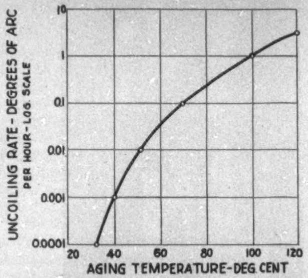


Fig. 10—Effect of Aging Temperature on the Rate of Uncoiling of Spiral Springs

Same springs as described in Fig. 7

After the load was removed recovery was approximately two-thirds completed in 30 hours. The recovery action was allowed to continue undisturbed for 7 days. When the recovery time was plotted to a logarithmic scale the recovery curve formed a straight line as shown in Fig. 14. Projection of the recovery curve to the point of complete recovery gave a period of 42 days required to recover from the effects of a load sustained for 30 hours.

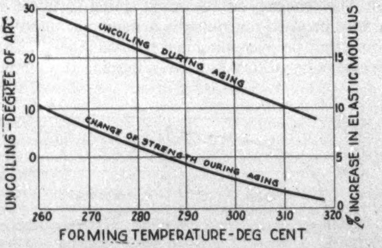


Fig. 11—Effect of Forming Temperature on Uncoiling and Increase in Elastic Modulus of Spiral Springs During Aging

Same springs as described in Fig. 7. Aged at 100 deg C for 15 hours

An extensive investigation of the effect of composition, load intensity, and load temperature was started in 1931. At the time of the preparation of this paper there had not been sufficient data collected upon which to form any conclusions.

## Conclusions

From these tests the following conclusions are drawn regarding the phosphor bronze spring materials used in the manufacture of spiral instrument springs.

1. Hereditary hysteresis is a minimum in instrument springs when the forming temperature is just below the softening point.

2. The softening temperature range for cold worked phosphor bronze spring material is very critical. Further, the softening temperature is lowered by an increase in the cold working of the material.

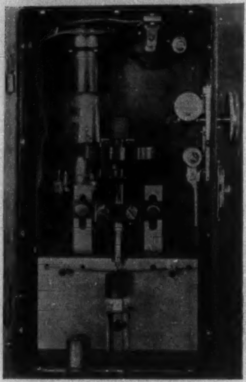


FIG. 12—GRID GLOW MICROMETER USED IN HYSTERESIS TESTS

3. The increase in diameter of the spiral spring as it is removed from the forming barrel indicates the relative intensity of the residual stresses in the spring.

4. The tendency of the spiral spring to uncoil and increase in elastic modulus is a minimum under conditions that produce minimum residual stresses. As in the case of hereditary hysteresis, forming at a temperature just below the softening point produces the minimum aging tendency.

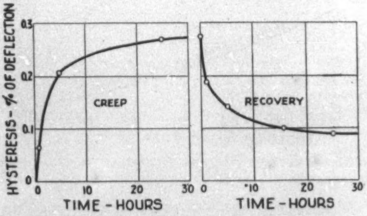


FIG. 13—HEREDITARY HYSTERESIS IN SPRING RIBBON

5 per cent nickel bronze strip, 0.109 in. wide, 0.016 in. thick, 84 per cent cold reduction in area. Formed flat at 300 deg C for 15 min. Loaded in bending at max. stress of 12,000 lb per sq in.

5. The aging tendency of properly formed springs can be eliminated by low temperature heat treatment.

6. Hereditary hysteresis is of a progressively continuous nature, and the creep rate is more rapid than the subsequent recovery rate.

Springs made in accordance with the information presented in this paper have been used in high grade indicating instruments with a marked improvement in performance. It is recognized that the details of the forming and aging process vary with the dimensions of the spring, and with the composition and mechanical condition of the spring material. However, the information given in this paper has been found to be sufficient for the development of manufacturing information for any of the usual instrument springs.

The author recognizes that the work described in this paper covers only one phase of the instrument spring problem. Additional information is needed on such subjects as the effect of composition, mechanical condition of the spring material, rolling practise, and temperature of loading on hereditary hysteresis and residual stresses. Also, the following bibliography may not be complete. If some of the results presented here have been obtained by others but not reported a contributed discussion on the subject will be welcome. It is hoped that this paper will bring out additional information of such value as will be reflected in further improvement in the performance of spring controlled instruments.

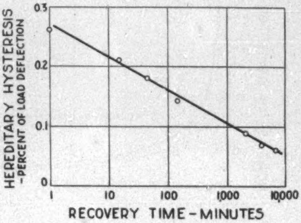


FIG. 14—HEREDITARY HYSTERESIS IN SPRING RIBBON

Same test as described in Fig. 13

### ACKNOWLEDGMENT

The investigation which developed the information included in this paper was conducted and financed by the Meter Engineering Department of the Westinghouse Electric & Manufacturing Company in cooperation with the Westinghouse Research Laboratories. The author is indebted to these agencies for permission to publish this paper.

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## Discussion

**Paul MacGahan:** Mr. Carson's paper is of great interest to all engineers who have been closely associated with the design of indicating instruments. In the writer's case this association began in 1898, following the earlier work of Shallenberger and Lange who were the first in America to produce commercial alternating-current instruments for switchboards.

In those early days there were enough troubles from temperature, frequency, and friction effects entirely to cover up the relatively smaller errors introduced by the springs. It was only as the electrical and mechanical features of the art progressed that it was realized that an instrument could be no more accurate than its control spring. Today the spring errors are as important as all the electrical errors combined. On the other hand, it should not be assumed that springs, as exemplified by the best instrument practice, were all wrong, but rather that the performance required of modern instruments requires a better knowledge of spring defects.

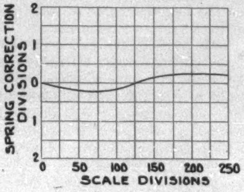

FIG. 1—THE VARIABLE RELATION BETWEEN DEFLECTION OF SPRING AND THE TORQUE REQUIRED TO PRODUCE IT, IS NOT GENERALLY REALIZED

(W. Bradshaw, Electric Journal, Vol. 3, 1906, p. 395.)

Earlier Westinghouse practice in the design of a-c instruments involved the use of 300 deg scale deflections, both in the switchboard line and in the "precision" line. This precision line still is in use after all these years as a secondary or transfer standard of reference by many who do not maintain a complete standardizing laboratory.

It is interesting to note that there was no appreciable spring trouble either in the old induction switchboard instruments or the precision instruments with their 300 deg deflections. This is of particular interest in the precision instruments where the spring effects would not be masked by electrical or mechanical inaccuracy in the instrument. In these instruments, a spring error of 1/50 of one per cent would be discovered if it were present. The excellent performance of the springs in these instruments was, no doubt, due to the fact that the springs were much larger in size and not rolled as thin as the springs in common use today. Even though the calculated stresses in the springs in modern instruments show a margin of safety higher than the margin of safety in the earlier 300 deg scale instruments, problems involving stability are more pronounced because of temperature conditions and other facts now brought out in this paper.

Is it not possible that in the thin springs size effects are encountered? Since residual stresses are associated with crystalline structure rather than molecular structure it seems reasonable to suspect that the relation between the thickness dimension of the spring ribbon and the average grain size across the section is approaching some critical condition in the thinner springs.

There is an interesting condition brought out by our practice in springs for precision instruments. These instruments use two springs, both mounted so as to wind up with increasing loads. The reason for adopting winding of both springs was purely experimental as the early day tests showed a better performance than when both springs unwound or when one spring unwound and the other wound up. It now appears from this paper that there was a real basis for these results since in the winding direction the external load stress on the springs is opposite in direction from the residual stresses and the deflection rate of the springs would be more uniform.

Another interesting point is that the presence of residual stresses as disclosed in the paper suggest a rational view of a long-known peculiarity in the deflection rate of springs. As early as 1906[1] the curve reproduced in Fig. 1 was published showing the characteristic deviation of the precision meter spring. This deviation might be explained as arising from the combination of load stresses and residual stresses. Assuming that residual stresses are of an appreciable magnitude as compared to the load stress, during the initial portion of a gradually applied load the spring deflection would be decreased slightly by the residual stresses. As the load stress increased, the residual stresses would have less effect so that the deflection curve of a single spring would appear as shown.

This explanation of the peculiar deflection rate is strengthened by the fact that the combined deflection curve for two springs can be varied by placing the two springs under slight initial tension, in which case one spring is wound up slightly and the other one unwound the same amount. In the residual stress conceptions the two springs when subjected to load operate at different points on the deflection curve so that the deviations in the combined deflection rates are compensated.

**A. B. Smith:** The success of the neon lamp as a detector of light pressure contacts led the writer to question the whole matter of the use of the telephone receiver for the same end. The latter is commonly used with low emf—1.5 volts or a little more. The most commonly used receiver is the operator's receiver, which has a winding of 80 to 125 ohms, direct current. Now, the neon lamp naturally uses 110 volts. If the telephone receiver were used with 110 volts and its coils wound to a high impedance, comparable to the emf used, how would it compare with the neon lamp?

Accordingly, the writer tested the matter, February 9 and 10, 1932. The neon lamp was rated at 2 watts on 110 volts. The telephone was a radio headset (2 receivers) whose total direct current resistance was 2,200 ohms. The commercial source of direct current had a pressure of 115 volts; the test circuit included, in series with the d-c source, a resistor, and a good contact key, and the device to be tested as an indicator. The work was done in a laboratory that was perhaps a little more noisy than the usual laboratory, and with north windows for illumination.

This particular neon lamp had a limit of about 59 megohms. Beyond this it would not light. At 59 megohms there was a distinct glow but it had to be viewed in a dark box. It seemed to be too weak for general use. The radio headset gave clear and unmistakable clicks at each closing of the key up to and including 700 megohms. Beyond this the writer did not have the means to go. There was no confusion caused by residual charge on the key, provided by opening the circuit elsewhere.

Both the neon lamp and the high resistance telephone receiver have a place as detectors of contact. Each has its own peculiar advantages. The telephone leaves the eye free from observations, leaving the ear to pick up the indication. The neon lamp may be used in ultra-noisy places, where the telephone click could not be heard. It is gratifying that the grid glow micrometer has been brought to our attention, and that the telephone receiver has promise of larger utility than before.

**Howard Scott:** It is quite generally known that metals creep, that is, flow under constant low loads, at high temperatures, but it is not so well known that they do so at normal temperatures. The effect is, of course, extremely small at room temperature and important in but a few cases, among which is that of precision springs. However, it is there a determining factor in the selection and treatment of metal for such uses. It is so small that an extremely sensitive test method is required to detect it. A highly satisfactory test method has been developed by Mr. Carson following the principles outlined by the writer.[2]

The author's tests on flat strips rather than coiled springs are of particular interest because they eliminate an important variable, residual stress, whose effects are difficult to distinguish from those of other factors. Obscure phenomena are often attributed, rightly or wrongly, to residual stresses that are certainly present in spiral springs. Consequently, it may be pertinent to examine closely their possible effects on spring performance.

Stresses remain within a spring released after the hot-forming operation due to the fact that the plastic yielding necessary to shape the spring does not vary linearly across the thickness of the spring strip. These stresses are commonly called residual stresses. Their intensity usually is a maximum at the surface where they have the greatest effect on spring performance. At the surface they are of opposite sign from the forming stresses causing the plastic yielding necessary to produce the desired spring curvature; that is, the stress is compressional on the convex surface of the spring, and tensional on the concave surface.

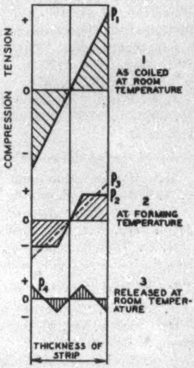

Fig. 2—Idealized Distribution of Axial Stresses During Forming of Flat Strips Into Spiral Springs

The manner in which residual stresses develop on hot-forming is illustrated by Fig. 2. It is assumed for the sake of simplicity that the stress-strain curve for the metal while hot consists of two straight lines, one representing loading to the yield point, $p_2$, and the other beyond the yield point. Deformation is assumed to continue indefinitely under the yield point load. On this basis, the three significant stresses defined by the figure are related as follows:

$$\frac{p_3}{p_1} = \frac{p_2}{2p_1}\left[3 - \left(\frac{p_2}{p_1}\right)^2\right]$$

The residual stress at the surface where it is most important is $p_3 - p_2$ and of opposite sign from $p_3$. These relations give, of course, only apparent values of the residual stresses, but the values are not enough different from what would be obtained were the true stress-strain curve used to modify any conclusions drawn here from them.

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[1] Wm. Bradshaw, "Maintenance and Calibration of Service Meters," *Electric Journal*, vol. 3, 1906, p. 395.

[2] H. Scott, "High Temperature Characteristics of Metals as Revealed by Bending," American Society for Testing Materials, V. 31, p. 129 (1931) Part II.

As the temperature of the spring metal is raised its yield point falls from around 100,000 lb per sq in. at room temperature to a very low value at the highest permissible forming temperature. The equation just given shows that as the yield point is so lowered, the residual stress at the surface which remains after release of the cooled spring must first increase from zero to a maximum when the yield point hot has dropped to about 60 per cent of the maximum applied stress, $p_1$, and thereafter falls as the yield point is decreased by higher temperatures. The residual stress never exceeds half the yield point at the forming temperature.

The manner in which the apparent yield point varies with forming temperature may be deduced from the data given in Fig. 7 and the equation. The initial forming stress at the surface, $p_1$, is about 86,000 lb per sq in. which is below the yield point of the cold metal. At the forming temperature, the yield point is temporarily much lower and may be estimated from the diameter of the spring as formed. It is of the order of 18,000 lb per sq in. at 255 deg C and 3,000 lb per sq in. at 320 deg C as calculated from the equation given here. Thus, the residual stress in the freed springs is lower, the higher the forming temperature within this range of forming temperatures. The degree of unwinding also diminishes with increasing forming temperature so Mr. Carson's suggestion of a direct relation between uncoiling and residual stress is plausible.

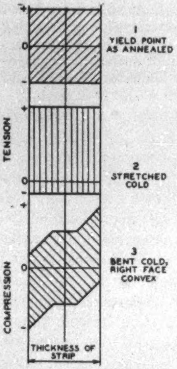

Fig. 3—Distribution of Yield Point Within a Metal Strip Produced by Plastic Deformation Under Tensile Loading and Bending

The magnitude of the apparent residual stress at the surface from the preceding data is 8,600 lb per sq in. after forming at 255 deg C and 1,500 lb per sq in. after forming at 320 deg C. It is not conceivable that stresses of this magnitude can produce the progressive unwinding observed by Mr. Carson which is many times the creep that would be observed in strips free from directional effects of forming. Consequently, one must look to some other factor in spring preparation for an explanation of unwinding.

It is well established that overloading in tension to the extent of producing appreciable plastic deformation lowers markedly the yield point in compression and *vice versa*. This effect taken together with the residual stresses offers a reasonable explanation of the phenomenon of unwinding. Fig. 3 shows by idealized drawings how the yield point within an annealed metal strip is modified by tensile deformation and bending. We do not know that the effects will be so notable when a cold worked metal is deformed or when deformation is produced hot as on spring forming, but suspect that they are both appreciable.

Assuming that the effects of plastic deformation illustrated by Fig. 3 apply to cold-worked metals deformed at forming temperatures, we have an obvious explanation for unwinding. The compressional residual stresses that appear at the convex surface of a spring upon release after forming may well reach an intensity equal to or greater than the effective compressive yield strength of these outer fibers which has been greatly lowered by the tensile plastic deformation previously applied during forming. Even if the residual stress approaches near the value of the modified yield point, appreciable plastic deformation may be expected. The direction of flow is such as to produce unwinding of a spiral spring.

Of the two factors that may modify the yield point as indicated, one probably is dominant. Which is dominant cannot be decided from the limited experimental data available, but may be determined by observations of spring creep under normal loading. If the dominant factor is cold-working, the rate of creep should be nearly the same for loads that uncoil as for those which cause the spring to coil to a smaller diameter. If, however, hot-forming is the dominant factor, the creep with unwinding loads should be much greater than with winding. Perhaps, Mr. Carson has made some observations on the rate of creep of springs loaded in both directions which will answer this question.

**H. B. Brooks:** Mr. Carson's paper is a welcome contribution to instrument-spring literature, which has been notable for its meager performance data and utter lack of information on the making of good springs. Fortunately, the idea that secrecy in such matters is necessary seems to be passing. The manufacturer who publishes the results of research work, undertaken to improve his product, produces a desirable impression in the mind of a discriminating purchaser.

The most important of all electrical indicating instruments is the wattmeter. It serves as a transfer instrument in the checking of portable a-c watthour meters in terms of the fundamental d-c standards, and it has been found to be the most accurate means for measuring the electrical output of generating units in water-rate acceptance tests. Such design details as the form and arrangement of wattmeter windings, compensation for the inductance of the windings and for temperature changes, and means for shielding, have been carefully studied. But with all of these details at their best, the performance of the wattmeter can be no better than that of its springs, and this is still short of being satisfactory.

The increase in the elastic modulus of springs, reported by Mr. Carson, explains the phenomenon recently shown by a wattmeter of the highest grade, originally adjusted by the maker to have errors not over 0.1 per cent of full scale value. The wattmeter reads low by 0.25 per cent on all ranges; the resistances of its circuits had their certified values, within very close limits, and the instrument showed no signs of overload or other abuse. The only reasonable explanation is that in the years since the instrument left the factory the stiffness of the springs had increased by 0.25 per cent.

An increase of temperature of 1 deg C reduces the stiffness of a phosphor bronze spring about 0.04 per cent. While the effect of this change can be compensated, it would be very desirable, especially for wattmeters, to have springs of high quality in other respects with a much lower value of temperature coefficient of stiffness. The use of phosphor bronze is almost as old as the art of making commercial electrical instruments. With the enormous increase in specialized alloys to give previously impossible performance in almost every other line of manufacturing, it seems strange indeed that we cannot have new and much better alloys for the making of instrument springs.

**R. W. Carson:** Improvements in sensitivity of electrical instruments have generally been obtained by reducing the weight of the moving element and using springs of thinner section and lower torque. This trend toward smaller and smaller dimensions in springs may be in part responsible for the greater significance of hysteresis effects, as Mr. MacGahan suggests. Also, his explanation for the non-linear deflection rate seems to account for this effect very well. With a hand-marked dial as used with most sensitive electrical instruments this effect would not readily be observed.

Data given in this paper obtained by the use of the bend test, developed by Mr. Scott, in conjunction with the recording grid glow micrometer apply only to flat ribbon. Although serving to duplicate stress, temperature, and load conditions in instrument springs this test method has not been applied to spiral springs. Such information as has been obtained on formed spiral springs is of doubtful value because of the test variables introduced by friction and inertia in the rotating member supporting the spring. Therefore, no data are available to show the relative effect of cold working and forming in introducing residual stresses. Tests on flat ribbons of cold worked phosphor bronze heated to 300 deg C for 15 minutes show that the hysteresis before heat treating is 10 to 30 times the hysteresis after heat treating. Residual stresses of considerable magnitude therefore are present in the spring ribbon before forming.

For anyone concerned with inelastic effects in spring materials, the stress analysis given by Mr. Scott is fundamental to the problem. From the procedure used to evaluate these residual stresses it is apparent that the problem is one for the engineer, not for the man in the shop.

To Mr. H. B. Brooks, the author is indebted for further evidence of the aging of springs at normal temperatures. Information given in this paper shows how this unstable effect can be eliminated in the manufacturing process, as well as removed from instruments in service.

As to the relative importance of the spring material and the manufacturing process in controlling spring performance, residual stresses appear to be the principal cause of aging and hereditary hysteresis, and residual stresses are controlled by the manufacturing process. The forming temperature which results in minimum residual stresses is in a critical range just below the softening temperature, which in turn varies with the cold working in the material. However, the expansion of the spiral spring as it is removed from the forming barrel is a minimum at the forming temperature producing the minimum residual stress. Springs formed at this temperature are further improved by an extended low temperature stress relief anneal.

For the springs shown in Fig. 7 the manufacturing operations, as established by the data in Figs. 8, 9, and 11, are as follows:

*Forming* at 300 to 310 deg C in air oven holding at temperature for 20 minutes. Maximum expansion of the spring when removed from the barrel—15 per cent.

*Aging*—Heat in air oven at 100 deg C for 24 hours. Aging follows last manufacturing operation.

Similar manufacturing data can be determined for other spiral springs, but the details will depend on the size of the spring, the spring material, and the cold working introduced in drawing and rolling. Expansion of the spring as it is removed from the spring forming barrel combines all three of these variables, and therefore provides a convenient and rapid means for setting up the manufacturing operations that produce a minimum of aging and hereditary hysteresis.

# A Portable Oscillograph With Unique Features

BY KIRK A. OPLINGER*

Associate, A.I.E.E.

***Synopsis.****—This paper describes a simplified portable oscillograph having a number of new optical and electrical features. The optical system, which consists of a combination of cylindrical lenses with axes at right angles, is designed to permit simultaneous viewing and photographing. A continuous time axis for both the viewing screen and film is secured by means of a small, variable speed, revolving mirror.*

*New galvanometers have been developed which have electromagnetic damping instead of the usual oil damping. These galvanometers are very rugged and have been built for recording frequencies as high as 14,000 cycles per sec.*

*The oscillograph is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments. The compactness and portability of the instrument can be seen from its over-all dimensions which are 8 × 11½ × 11 in. and from its total weight, which is approximately 18 lb.*

## INTRODUCTION

During the past few years, numerous applications have been opened to the oscillograph in connection with radio broadcasting and the use of vacuum tubes for industrial purposes. Outside the field of electrical engineering, the oscillograph has been used for acoustical studies and for the measurement of vibrations, accelerations, and pressures. In many of these applications, the oscillograph has not only simplified the development work, but it has often furnished data that could be obtained in no other manner.

In designing an oscillograph for applications such as mentioned above, simplicity and ruggedness are of primary importance, as the instrument will not generally be used by an experienced oscillograph operator. The size of the oscillograph and the ease of making visual observations are also important since the oscillograph will be used much the same as an instrument to make comparative measurements of amplitude, phase, frequency, or wave shape. To meet all of these requirements, an entirely new oscillograph, differing greatly from previous designs, has been developed using a new type of optical system and galvanometer. This new instrument may be used as conveniently as an ordinary voltmeter or ammeter, and has other characteristics which will extend the range of application of oscillographic instruments.

## DESCRIPTION

A general view of the oscillograph is shown in Fig. 1. The instrument is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments. The oscillograph is very compact as shown by its over-all dimensions which are 8 × 11½ × 11 in. Its total weight is approximately 18 lb.

A top view of the panel is shown in Fig. 2. Terminals for the two galvanometers are located at the lower left and right hand corners of the panel. Each galvanometer has a single switch for selecting the desired multiplier or shunt resistor. The values marked on the panel give the approximate d-c voltages and currents for a deflection of one inch. Both galvanometers may be used for measurements of potentials up to 300 volts or currents up to 10 amp without the use of external resistors. The control switches have a stop to prevent the operator from accidently switching to the current side when connected to a voltage circuit. However, no damage will result to the instrument if this mistake is made, since both the resistors and galvanometers are protected by fuses.

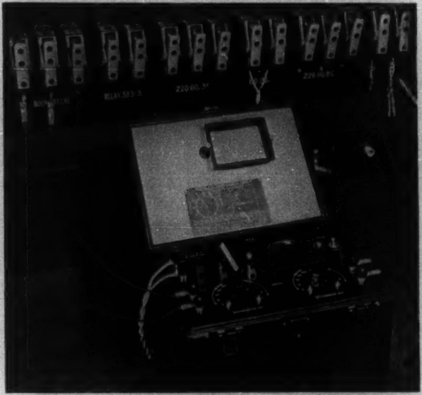

FIG. 1—GENERAL VIEW OF OSCILLOGRAPH

In the upper left hand corner of the oscillograph are two controls which permit adjusting the zero position of each galvanometer. The "timing" knob in the opposite corner of the panel varies the timing axis, as will be explained later, and thus controls the number of cycles visible on the viewing screen.

Both film and viewing screen are stationary and in position for use at all times. When it is desired to take a photograph of any recurrent phenomenon, it is only necessary to press the "expose" button near the center of the panel. This button opens a shutter to the camera, and at the same time, places an overvoltage on the oscillograph lamp. Provision has been made to use either a standard cut film holder or pack with 2¼×3¼-in. film in a manner similar to that of an ordinary camera.

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*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

### Optical System

Simultaneous viewing and photographing is made possible by the optical system shown in Fig. 3. This system also gives an optical multiplication of the galvanometer deflection, thereby making it possible to obtain the equivalent of a long optical lever in a short space. Referring to Fig. 3, the slit is illuminated by a standard 6-volt 32-cp automobile headlight lamp whose filament is imaged on the galvanometer mirror by a small condensing lens. The lenses $L_1$ and $L_2$ are cylindrical with their axes at right angles to the axes of the cylindrical lenses $L_3$ and $L_4$. Optical multiplication is obtained by means of the lenses $L_1$ and $L_2$. The lens $L_1$ gives a reduced image of the slit directly in front of the lens $L_2$. This image, together with any motion imparted to it by the galvanometer mirror, is then enlarged by the lens $L_2$ on to the film. The size of the image on the film, in the vertical direction, is therefore fixed by the width of the slit and the overall magnification of the lenses $L_1$ and $L_2$. The other dimension of the image is determined by the height of the slit and the magnification of the lenses $L_3$ or $L_4$ which focus on the film and screen respectively.

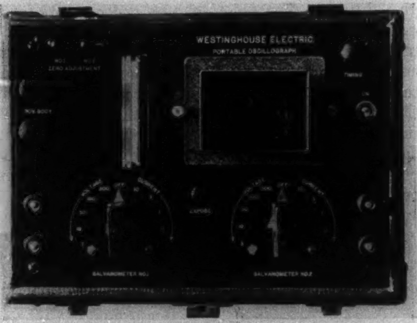

Fig. 2—Oscillograph Panel

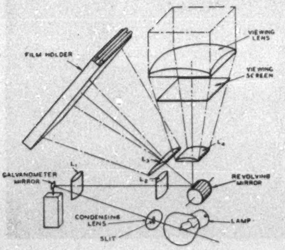

Fig. 3—Optical System

To secure a continuous time axis, the number of faces on the revolving mirror, and the angles subtended by the film and viewing screen, have been chosen so that there is always a spot of light entering on both the film and screen just as the previous spot is leaving. This arrangement makes it possible to study transient phenomena without the possibility of a transient occurring at a time when the screen is dark.

Directly above the viewing screen is a spherical lens, so placed that it gives an enlarged virtual image which is comparable in size to the image on the film. Without this lens, the image does not appear equally bright at all points on the screen. The lens corrects for this and also gives greatly increased brilliancy which is sufficient for viewing even in a brightly lighted room. If desired, the viewing lens with its screen may be removed and replaced by a large curved screen which is shown mounted on the lid in Fig. 1. This arrangement makes it possible to trace wave forms and to use the oscillograph in a darkened room for such purposes as classroom demonstrations before a group of students.

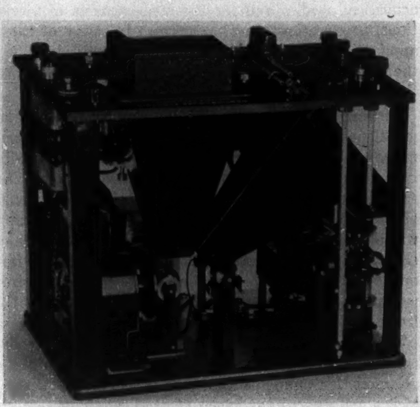

Fig. 4—Inside View of Oscillograph

An inside view of the oscillograph is given in Fig. 4, showing the arrangement of the different parts of the optical system. The small revolving mirror is driven by the friction between a wheel on the mirror shaft and a face plate mounted on the end of the motor shaft. The speed of the mirror, and hence the timing on the screen, is varied by sliding the motor back and forth to change the driving radius.

### GALVANOMETERS

The galvanometers used in the oscillograph are as shown in Fig. 5. They are of the moving iron type with a balanced armature.[1] This design results in a very rugged construction which can withstand large overloads without damage and is particularly suitable for portable work. These galvanometers were originally developed for sound recording systems and have proved to be very satisfactory for this purpose.[2] The arrangement of the armature, poles, and coils is shown in Fig. 6. Permanent magnets of cobalt steel are used to supply a steady flux in the four air gaps. When current flows in the coils, the flux in one pair of diagonally opposite gaps is increased, while the flux in the other pair is decreased, resulting in a force couple which tends to rotate the armature about its vertical axis. The restoring force for the armature is furnished by its support.

The construction of the armature and method of support is shown in Fig. 7. It will be noted that the support has a 90 deg twist at the top which places the armature at right angles to the flat, tapered stem. This construction gives the desired torsional stiffness for the armature, and at the same time, furnishes a high bending stiffness to keep the armature centered in the air gap. The mirror is mounted on a short stem extending above the armature. It is desirable to have this mirror large, since it is one of the limiting factors in the amount of light that is available on the oscillograph viewing screen and film. On the other hand, the mirror size cannot be increased indefinitely, since its inertia must be comparable to that of the armature for optimum overall performance. The mirror shown in Fig. 7 is 1/8×5/32 in. and has approximately fifteen times the area of an ordinary oscillograph galvanometer mirror.

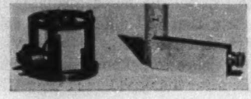

FIG. 5—MOVING IRON TYPE GALVANOMETER

In a galvanometer of this type, the force factor, or force per unit current, is a measure of the sensitivity. Since this force factor varies directly with the flux density in the air gap it is desirable to have as large a steady flux as possible. With the balanced armature type of construction, this is possible without saturating the armature, since the flux passes directly across the gap, and does not travel the length of the armature. However, an increase in steady flux results in a magnetic reduction in the net armature stiffness, and this reduction must be less than the mechanical stiffness of the armature, if the armature is to remain stable in the gap. This latter requirement was a serious limitation in the design of the balanced diaphragm receiver where the net diaphragm stiffness must be fairly low in order that the unit could cover the desired frequency range. However, in the case of the galvanometer, the armature stiffness must necessarily be relatively high in order to obtain a high resonance frequency and therefore, a large steady flux may be used to secure maximum sensitivity.

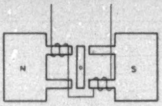

FIG. 6—BALANCED ARMATURE CONSTRUCTION

The galvanometers, as used in the oscillograph, are designed for twenty ohms impedance and have a sensitivity of 0.10 amp d-c per inch deflection. This sensitivity depends, of course, upon the frequency range, the above sensitivity being for a galvanometer with a 5,000 cycles per second response. The frequency range may be extended simply by increasing the torsional stiffness of the armature support and galvanometers of this type have been used for recording frequencies as high as 14,000 cycles per second. Galvanometers of this range, however, have much lower sensitivity. In contrast to other types of galvanometers, the moving iron type becomes more rugged as the frequency range is extended.

The damping of a galvanometer is also an important factor in determining frequency response. If there is only a slight amount of damping, deflections near the resonance frequency will be greatly magnified, since the galvanometer sensitivity is much greater for frequencies in this region. No matter how high this resonance frequency is placed, there is always the probability that high frequency components of the applied wave will occur in the range of resonance. To prevent accentuation of these components, the response of the galvanometer at resonance must be reduced by adequate damping. With the correct amount of damping, a galvanom-

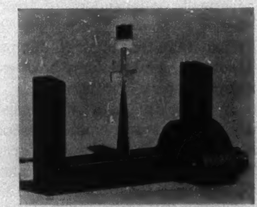

FIG. 7—GALVANOMETER ARMATURE AND SUPPORT

eter will have practically uniform sensitivity throughout its entire frequency range. This damping should remain constant regardless of time or temperature, so that there is no change in calibration. In most galvanometers, it is necessary to use some form of mechanical damping, such as oil or rubber, but with the moving iron type it has been possible to get sufficient electromagnetic damping to approach the above requirements closely. If a strong magnetic field is used, the motion of the armature at resonance will generate a back-voltage which will oppose the applied voltage to prevent any large deflections. The effectiveness of this back voltage is determined by the total resistance of the circuit.

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[1] This construction was suggested by C. R. Hanna who has published the fundamentals of design, for moving iron systems, in his paper "Design of Telephone Receivers for Loud Speaking Purposes," *Proc. I.R.E.*, 1925, p. 437-460.

[2] "The Mitchell Recording Camera Equipped Interchangeably for Variable Area and Variable Density Sound Recording," C. R. Hanna, *Trans. Soc. Motion Pic. Engrs*, v. 13, 1929, p. 312-6.

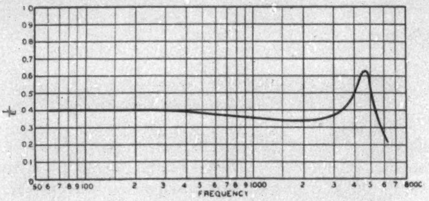

Fig. 8—Galvanometer Frequency Response

A typical response curve for the galvanometer used in the oscillograph is shown in Fig. 8. Although the damping obtainable with electromagnetic systems as used in this galvanometer is somewhat less than the desired value, it should be emphasized again that it is practically independent of temperature, and the frequency response characteristic is therefore more satisfactory than that of an oil damped galvanometer which at low temperatures may be over-damped and at higher temperatures under-damped.

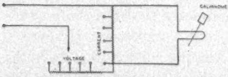

Fig. 9—Diagram of Galvanometer Circuit

In order to use a single galvanometer for making both current and voltage measurements, the circuit shown in Fig. 9 was devised for use in the oscillograph. This circuit makes the galvanometer response independent of the resistance of the external circuit and also provides a simple arrangement for making tap connections on the shunt and multiplier resistors. When making current measurements, a small resistance having a number of taps is permanently shunted across the galvanometer. The taps give the desired current range and the value of the shunt is such as to give the desired frequency response. It can be shown that this response is the same for any tap position. For making voltage measurements, another resistor is connected in series with the current circuit. This latter resistance has taps to cover the voltage steps, and is arranged so that on the lowest voltage tap, there is still sufficient resistance to give essentially a constant current to the shunted galvanometer circuit.

## CONCLUSIONS

The portable oscillograph, which has been described, was designed to meet a large variety of general engineering applications. The following unique features make this instrument especially adaptable to such applications.

1. Simultaneous viewing and photographing.
2. A continuous time axis furnished by a small revolving mirror the speed of which is variable.
3. A new type of galvanometer with electro-magnetic damping and high frequency response.
4. An optical system which magnifies the galvanometer deflections and which give a brilliant trace that can be observed in a brightly lighted room.
5. A simple method of taking photographs similar to an ordinary camera.
6. A large viewing screen for making tracings or for giving demonstrations to a group of persons.
7. Simplicity, compactness, and ruggedness comparable with the average electrical indicating instrument.

Although this oscillograph is a research development product, it will be made available in the near future in a form that will differ only in minor details from the instrument described.

The author wishes to acknowledge his indebtedness to C. R. Hanna for many valuable suggestions in connection with the above development, to W. O. Osbon who designed one of the earlier types of galvanometers, and to S. Sentipal for working out many details in the mechanical design. Credit is also due other members of the research laboratories and shop organization who have made contributions to this development.

## Discussion

**Everett S. Lee:** Mr. Oplinger's paper describing a portable oscillograph makes it appropriate at this time for us to look both backward and forward in the oscillograph art. The earliest design of oscillograph which we could find was that of Blondel's in 1891, just 42 years ago. A later design was of 1900, and one by Duddell of 1898.

The first electromagnetic oscillograph of the General Electric Company was produced in 1904. For years this oscillograph was quite generally used until the advent of the permanent magnet galvanometer oscillographs a few years ago. Such a galvanometer is completely self-contained and is the element for all of these oscillographs, the popular 6-element oscillograph, the 2-element with large tracing screen, and the portable 2-element oscillograph. The portable 2-element design has been a most popular oscillograph for the past three years, having been described before the Institute May 7, 1930.[1] This is for viewing recording phenomena, with photography of the same obtained with the addition of the film holder, and for photographing transients with the continuous drive film holder using films 30 in. long at a variety of film speeds. The development of this continuous drive film holder as an attachment to this portable oscillograph has considerably extended the field of usefulness of this instrument. This oscillograph is in the portable class as is the instrument described by Mr. Oplinger, though extending the photography range to include the photography of transients, which, it is the writer's understanding, the Oplinger design does not do. The galvanometers of this oscillograph are of the conventional oil-damped type, which permits the taking of accurate transient records.

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[1] See *A New Portable Oscillograph*, C. M. Hathaway, A.I.E.E. Jl., Aug 1930, vol. 49, No. 8, pp. 646-649.

The field of automatic oscillographs has been totally served by a design[2] that looks different from the previously described instruments because it was designed specifically for automatic recording of transmission line performance and the like. In this field it has demonstrated its uniqueness. This is the most human of the oscillographs. It starts itself, due to a surge, and keeps going until the surge is reduced. It then stops and waits for another. It operates within ½ cycle of a 60-cycle wave, and produces an oscillographic record on bromide paper.

The important field of cathode ray oscillographs must not be forgotten. DuFour was the pioneer in this art. In this oscillograph the moving element is a beam of electrons in an evacuated tube. One design is of the high-voltage type, looked upon mostly as a laboratory instrument, but in this form used in factory and field alike. On one of its most famous exploits it was taken into the mountains of Pennsylvania where the first wave form of a lightning surge on a transmission line to be photographed in the United States was obtained. Another design provides a cathode ray oscillograph with a sealed evacuated tube for lower voltage work. The use of vacuum pumps has been eliminated, which is a boon to the operator. This feature will, no doubt, some day be extended to the higher voltage range for general purpose impulse testing which will considerably simplify the technique in this field.

We all recall the point-by-point plotting of wave forms, and instruments are available that permit a curve to be traced simply by following the pointer of an indicating instrument by hand. We now have the photoelectric recorder[3] to do this same thing automatically with the hand replaced by a beam of light. Simple wave form records have been obtained with a photoelectric recorder in the form of an ink record on a paper chart, thus eliminating photography. The obtaining of records directly without the need for photography will represent a most important advance in oscillography. The next few years should see this an accomplished fact.

The many applications of oscillographs would fill many pages of the most interesting material. Records taken on bromide paper with the 6-element oscillograph with the continuous drive film holder are of particular interest.[4] Records may be taken up to 100 feet in length. Such records show the performance of an electric locomotive over a 100-mile division. Each inch of record represents 15 rail lengths. On locomotive or ship, in factory or field, in laboratory or class-room oscillographs designed to fill a multiplicity of needs are being successfully used.

Much of the electrical progress of the century has been due to the oscillograph. The achievement of making these designs available, the foresight in using oscillographs as an invaluable tool, and the opportunities for advancement disclosed through use, have all contributed to this progress.

It would not be appropriate to close this discussion without referring to two men whose contributions to oscillography have been outstanding, the late Doctor L. T. Robinson of the General Electric Company and the late J. W. Legg of the Westinghouse Electric and Manufacturing Company. Both of these men have been taken from us and the art has been the loser. Men such as Mr. Hathaway and Mr. Oplinger are carrying on. Their activity compensates for this loss, which is the way progress works.

**Kirk A. Oplinger:** The continuous drive film mentioned by Mr. E. S. Lee has been used on many different types of oscillographs for a number of years and it is planned to add such an attachment to the instrument described in the paper. This can be done simply by deflecting a portion of the light beam, just before it strikes the revolving mirror, upon a continuous film drive attachment. (See Fig. 3 of the paper). Since the deflected light will only be that portion which normally sweeps the stationary film holder, the oscillograph may still be used for simultaneous viewing and photographing.

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[2] *An Automatic Oscillograph*, C. M. Hathaway and R. C. Buell, Trans. A.I.E.E., March 1932, vol. 51, pp. 222-225.

[3] *The Photoelectric Recorder*, C. W. LaPierre, Trans. A.I.E.E., March 1932, vol. 51, pp. 226-233.

Also "An Improved Photoelectric Recorder," C. W. LaPierre, *Gen. Elec. Rev.*, vol. 36, No. 6, pp. 271-274.

[4] "Continuous-Drive Record Paper Holder for Oscillograph," C. F. Fischer, July 1933, Vol. 36, No. 7, pp. 328-329.

# The Expulsion Protective Gap

BY K. B. McEACHRON* I. W. GROSS† and H. L. MELVIN‡
Member, A.I.E.E. Associate, A.I.E.E. Fellow, A.I.E.E.

THE expulsion protective gap is an outgrowth of the fused grading shield[1] in which a fuse in series with a gap is connected in parallel with an insulator string to prevent the flashover of the string due to lightning. The essential elements of the expulsion protective gap are shown in Fig. 1 and consist of a gap inside a fiber tube whose length is such that flashover always occurs inside the tube across the internal gap. The function of the external series gap is to reduce the stress due to continued application of system potential to a value that will not allow carbonization of the tube. The tests made show that the external gap has little part in interrupting the flow of system current through the tube following a lightning discharge.

## OPERATION

Unlike the fused grading shield the expulsion gap is capable of many operations without servicing since there is no fuse in the circuit to be replaced. During the operation of the expulsion gap pressure is developed within the tube which if too great will burst the tube and if too small allows the power arc to continue without extinction so that the tube eventually fails. Thus it is seen that the expulsion protective gap has a maximum and minimum current rating. The established current ratings for expulsion protective gaps rated from 13.8 kv to 230 kv are shown in Table I. Other current ratings could be provided but it is felt that those given will meet most conditions of service.

For ratings 115 kv and below a single tube is used, as illustrated in Fig. 1, while two tubes are used in series for higher voltage ratings. The 138-kv tube used in most of the Glen Lyn tests to be described later was of the two tube type discharging at the middle and at one end. The vents may be arranged to discharge the gases at an angle to the fiber tube if desired. Since discharge gases emerge with considerable violence from the vents in the tube and extend for considerable distance it is desirable to so mount the expulsion gap that gas or flame from the line end of the tube cannot come in contact with grounded metal structures or discharge from the ground end of the tube come in contact with live parts.

## PROTECTION

Table I also shows the number of insulators and point gap in inches which can be protected, indicating that most steel tower lines and probably all wood pole lines without bonded hardware have sufficient insulation so that protection may be secured with a good factor of safety. These data were secured from tests made on ½-5, 1½-40 and front of the wave tests in which the potential rises at the rate of approximately 3,000 kv per microsecond. It seems probable that most of the operations will be on the front of the wave since as a rule a tube would be located at the point of inception of the discharge on the line.

## APPLICATION

The expulsion protective gap may be applied at any point where the minimum current is not less than the minimum rating of the tube and where the maximum rating is not exceeded. If the insulation is equal to or in excess of that shown in Table I protection will be afforded. In general, ungrounded circuits on steel tower lines cannot supply sufficient line-to-ground current to operate the expulsion gap properly if the phase-to-phase short-circuit current is to be interrupted also.

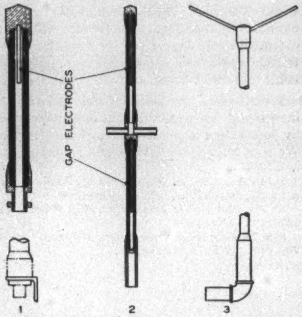

FIG. 1—EXPULSION PROTECTIVE GAPS

1—Single tubes for use 115 kv and below
2—Double tubes for all ratings above 115 kv
3—Showing use of horns and also means of directing discharge

For wood pole lines where the insulation of the wood is available, the expulsion protective gap may be connected in parallel with each insulator and the insulator supports all connected together without making any connection to ground whatever. (Fig. 2A.) This arrangement will prevent line-to-line flashovers over the insulator and will make it unnecessary for the expulsion gaps to extinguish the line-to-ground current except those few cases where power follow to ground takes place. Such a scheme is particularly adapted to ungrounded circuits but may be used also for grounded neutral circuits, if desired.

There is evidence from experience in service to indicate that if a circuit to ground is established at approximately 2,000-ft intervals, there is little probability of lightning damaging the entire length of the intermediate poles. For those poles where a path to earth is to be established a wire may be extended down the length of the pole and tied in to the intercon-

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‡Electric Bond and Share Co., New York, N. Y.

[1] For references see bibliography.

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TABLE I—EXPULSION PROTECTIVE GAP DATA

| Voltage ratings | | Short-circuit interrupting capacity ratings | | | | No. of insulators (5¾ in.) protected all waves | Approximate rod gap protected spacing in inches |
|---|---|---|---|---|---|---|---|
| Circuit rating | Max. perm. line-to-ground voltage rms | Minimum current rms | Maximum current rms | Three-phase symmetrical (system) | | | |
| | | | | Min. kva | Max. kva | | |
| 13.8 kv | 8.4 kv | 300 | 2,500 | 7,200 | 60,000 | 1 | 5 |
| | | 1,000 | 10,000 | 24,000 | 240,000 | | |
| 23.0 | 14.0 | 300 | 2,500 | 12,000 | 100,000 | 2 | 7 |
| | | 1,000 | 10,000 | 40,000 | 400,000 | | |
| 34.5 | 21.0 | 600 | 2,500 | 36,000 | 150,000 | 2 | 10 |
| | | 1,200 | 10,000 | 72,000 | 600,000 | | |
| 46.0 | 28.0 | 600 | 2,500 | 48,000 | 200,000 | 3 | 13 |
| | | 1,200 | 10,000 | 96,000 | 800,000 | | |
| 69.0 | 42.0 | 600 | 2,500 | 72,000 | 300,000 | 4 | 20 |
| | | 1,200 | 10,000 | 145,000 | 1,200,000 | | |
| 92.0 | 56.0 | 600 | 2,500 | 96,000 | 400,000 | 6 | 27 |
| | | 1,200 | 7,500 | 192,000 | 1,200,000 | | |
| 115.0 | 70.0 | 600 | 2,500 | 120,000 | 500,000 | 7 | 35 |
| | | 1,200 | 7,500 | 240,000 | 1,500,000 | | |
| 138.0 | 84.0 | 600 | 2,500 | 140,000 | 600,000 | 9 | 41 |
| | | 1,200 | 7,500 | 280,000 | 1,800,000 | | |
| 161.0 | 97.5 | 600 | 2,500 | 167,000 | 700,000 | 10 | 48 |
| | | 1,200 | 7,500 | 334,000 | 2,100,000 | | |
| 230.0 | 140.0 | 600 | 2,500 | 240,000 | 100,000 | 14 | 70 |
| | | 1,200 | 7,500 | 480,000 | 300,000 | | |

nection between the insulator supports and the three expulsion gaps. A fourth expulsion protective gap having a minimum current rating equal to the line-to-ground follow current expected may be inserted in the wire down the pole. (Fig. 2B.) To assure discharge through the tube the expulsion gap plus its connecting lead should span a length of pole equal approximately to three times the equivalent gap of the expulsion protective gap.

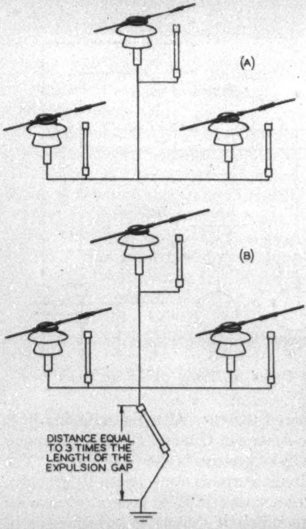

Fig. 2—Diagrammatic Sketch Showing Use of Expulsion Protective Gap on Wood Pole Line

A—With no connection to earth

B—Connected to earth through expulsion protective gap of lower current rating

With such a multiplex arrangement the expulsion gaps in parallel with the insulators must be able to interrupt the phase-to-phase short-circuit current while the tube in the ground circuit would only need to be able to interrupt the ground current. This multiplex arrangement is not readily adapted to circuits on steel towers, because it is of course necessary that the insulator support be free from ground.

On higher voltage grounded neutral circuits on wood using *H* frame construction the expulsion protective gaps may be mounted as shown in Fig. 8 with the metal support for the expulsion gaps grounded. Where ground resistances are high the circuits of Figs. 2A or 2B may be used.

If the circuit is on steel and has a ground wire it is probable that in most cases an expulsion gap will be found with the proper maximum and minimum current ratings, but if no ground wire is present tower ground resistances may in some cases be so high as to limit the current to a value which a tube, suitable for phase-to-phase operation, could not extinguish. In such a case it may be expedient to lower the ground resistance.

Two methods of mounting expulsion protective gaps in towers are shown in Fig. 3. The circuit on the left side of the tower makes use of two tubes mounted on the insulator string, while the circuit on the right employs expulsion gaps mounted on the arm below.

From the point of view of preventing interruptions to service due to lightning it is believed that the expulsion gap will give a performance equal to that expected of the ground wire, with low tower footing resistance, with perhaps the exception of the direct stroke to midspan. If ground wires are provided it is not necessary to have low tower footing resistance if the expulsion protective gap is used. On the other hand, if ground wires are not used the tower footing resistance must be low enough to permit sufficient current to flow to operate the expulsion gap. Economics and the service performed by the expulsion protective gap will determine its place among the various schemes of protection of transmission lines.

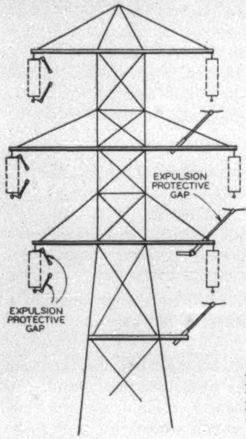

Fig. 3—Showing Two Methods of Mounting Expulsion Protective Gaps

When the factor of safety between the expulsion gap and the line insulation is not great, as in the case of steel tower lines, an expulsion gap on one tower will not offer any appreciable protection to insulation on adjoining towers. However, with wood pole lines where the insulation may be high, the expulsion gap will offer considerable protection to insulation on adjacent structures. This means that on wood pole lines considerable improvement may be expected if the gaps are installed on alternate structures, although equal performance on the steel tower line probably would require a gap on each structure. Service experience indicates a considerable degree of protection at distances as great as 1,000 ft to 2,500 ft on *H* frame lines.

When the gap operates on high current near its upper limit there is a certain erosion which increases the bore of the tube, and which has the effect of increasing both the high and low current rating of the tube. The amount of erosion is such that the life of the expulsion gap will generally be limited by its weathering rather than by the results of electrical discharge. As the result of discharge there is some burning of the electrodes also but this is not sufficient to result in any appreciable increase in gap length throughout the life of the tube.

It is possible that some of the lower current rated tubes may be destroyed by the severest of direct strokes, although these tubes have withstood, with no distress whatever, the maximum laboratory impulses which we have been able to produce.

## Field Tests on 138-Kv Expulsion Protective Gaps

The performance of the expulsion protective gap having indicated, on laboratory tests, its ability both to protect insulators against lightning flashover and also to interrupt power current, it was arranged to conduct staged field tests with the device on a 132-kv system where it would be called upon to interrupt short-circuit currents on an operating system fed by a large kva generating capacity. These tests were made in September 1932 at the Glen Lyn, West Virginia generating plant of the Appalachian Electric Power Company, representatives of the American Gas and Electric Company, the General Electric Company, and the power company cooperating in the work.

*System On Which Tests Were Made.* The one line diagram of the 132-kv system at Glen Lyn, where the tests were conducted together with the outgoing lines tying in with the American Gas and Electric Company interconnected 132-kv system, is shown in Fig. 4. The range of short-circuit currents (one phase to ground), possible at Glen Lyn, under different generator capacity at Glen Lyn and different switching arrangement of lines, was from 570 to 3,100 amperes symmetrical rms. Further calculations showed from 50 to 75 per cent of this current was supplied by the Glen Lyn machines,

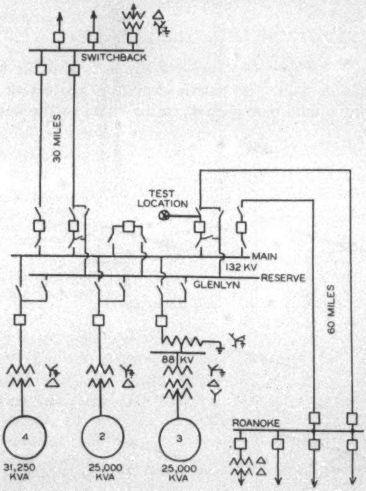

Fig. 4—Circuit Diagram—Tests Made at Glen Lyn

the balance being supplied from the interconnected system.

*Description of Expulsion Protective Gaps Tested.* The expulsion protective gaps tested were of the design shown in Fig. 1. Both single and double internal gap assemblies were used, the majority of the tests, however, being made on the two internal gap design. Provision was made to alter the length of internal gaps, tube diameter, and method of venting the tubes as the testing progressed. The overall length of the double gap tube exclusive of the arcing horn was approximately 7 ft, and of the single gap tube 5 ft.

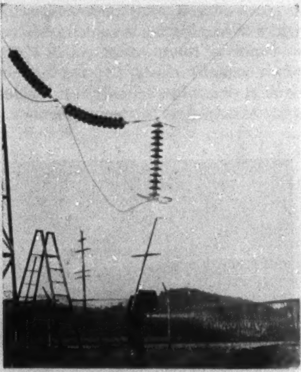

FIG. 5—EXPULSION PROTECTIVE GAP SETUP FOR TESTS AT GLEN LYN

76 kv to ground. 2,850 amp crest. Test No. 20. Expulsion gap is shown discharging through metal tube extensions for directing the discharge gases

*Field Test Setup.* For convenience of handling and observation, the tube assembly was mounted rigidly on a wooden post, with the bottom end of the tube grounded and about 3 ft above the ground. At the top end of the tube an external gap of approximately 10 in. (to the line conductor) was provided. The tube was mounted about 30 degrees to the vertical, which was the position considered if the tube later were actually installed permanently on the steel transmission towers, similar to that illustrated in the right of Fig. 3. The tube setup taken during one of the tests is shown in Fig. 5. In this illustration the expulsion gap is shown in its normal position, although for most of the tests the tube was inverted in order that the internal tube pressure at the normal line end of the tube might be measured. The pressure recorder is protected by a metal hood in the illustration.

Since impulse voltage was not available for breaking down the internal and external gaps on test, these gaps were short-circuited with 12 mil lead-tin fuse wire, and in test No. 41 three strands of this wire were used in parallel. While the presence of this wire in the internal gaps may not have seriously interfered with the normal performance of the tube in clearing the power arc, the existence of metallic vapor in the arc, due to the presence of the fuse wire, would tend to increase the possibility of the expelled gases causing a power arc outside the tube to grounded structures.

The short-circuit power arc in the tube simulated conditions which will occur at the time of lightning discharge through the tube when applied to protecting a transmission against lightning outages. There was produced, in every case, a single-phase (76-kv) short circuit through the tube to ground, the current being limited only by the reactance of the generators and line on the circuit, and the station ground resistance of 0.25 ohms.

Forty-one tests were made in all, forty with a setup similar to Fig. 5, and one with the tube mounted in a tower. Nine different combinations of tubes, internal gaps, and methods of venting were used. The tests included combinations of assemblies which were believed not only to be within the limits of rating of the tube, but also well outside the tube rating to determine the current breaking limits of the tubes, and to study the various factors affecting them.

*Test Data and Results.* The summarized test data are given in Table II. The important points brought out in these tests are as follows:

1. Crest power currents as low as 615 amperes and as high as 6,700 amperes were broken successfully on a 132-kv circuit (76 ft to ground) by the protective gaps in a time of from 0.37 to 0.88 cycles (based on 60 cycles per sec) without causing the oil circuit breaker to open.

TABLE II—SUMMARIZED TEST DATA ON 138-KV EXPULSION PROTECTIVE GAPS
Field Test at Glen Lyn

| Test No. | Glen Lyn generator kva | Miles of line from Glen Lyn | Calculated sym. rms s.c. amps[1] | Measured crest amps. interrupted | Duration of current cycles[2] | Line tripouts | Tube failures | O.C.B. tripped |
|---|---|---|---|---|---|---|---|---|
| 1 | 25,000 | 0 | 570 | 1,230 | 0.74 | 0 | 0 | No. |
| 2-10 | 31,250 | 130 | 650 | 615 to 1,300 | 0.41 to 0.78[3] | 0 | 0 | No. |
| 11-12[4] | 56,250 | 130 | 670 | 1,100 to 1,300 | 0.53 to 0.70 | 0 | 0 | No. |
| 13-23[4] | 56,250 | 60 | 1,460 | 2,050 to 2,850 | 0.49 to 0.88 | 0 | 0 | No. |
| 24-40[4] | 56,250 | 0 | 3,100 | 2,500 to 6,700 | 0.37 to 0.69 | 0 | 1 | No. |
| 41[5] | 56,250 | 0 | 3,100 | 5,900 | 0.55 | 0 | 0 | No. |

[1] Symmetrical rms short-circuit amperes calculated from system setup.

[2] Tests on 60-cycle system.

[3] Also one test each at 2.5, 4.5, and 8.0 cycles. Arc restruck in one case 1½ cycles after clearing in 0.78 sec.

[4] Two single internal gap tubes included in this group.

[5] This test on tube mounted on a line tower.

2. These short-circuit currents were in every case broken by the gaps on the first major zero point of the current wave except in four cases. In 1 of these cases the arc restruck 1½ cycles after clearing 1,270 crest amperes but immediately cleared again in 0.36 cycles, the crest current on the second clearing being 470 crest amperes. In the other 3 cases where the arc was cleared in from 2.5 to 8 cycles, the interrupted current was outside the tube rating as was predicted before the test was made.

3. The general design of the tube, as regards internal gap spacing, diameter, tube length, mechanical strength, and 60-cycle dry flashover appears to have been carried out in a manner which indicates the tube performance in service can be predicted with a reasonable assurance, and that it can be applied successfully to lightning protection of 132-kv lines.

4. The only tube which failed on test had an internal gap setting longer than is considered practical, in combination with the external gap, for protection of a 132-kv transmission line. Even in the case of this tube failure, where the tube burst, the short circuit was cleared by the tube, and the circuit did not trip.

5. The maximum measured pressure inside the tube at the time of discharge was 7,000 lb per sq in. This indicates that consideration must be given to the balancing of the gas discharge paths to prevent undue stress and distortion of the tube and its mounting hardware, when the tube is applied practically to a transmission line.

6. The performance of the expulsion gap does not appear to be affected appreciably by conducting the discharge gases from the tube through a length some 12 in. to 18 in. of pipe, and even by changing the direction of gas flow by 90 degrees. This feature may be of considerable practical importance if, in certain applications of the expulsion gap, it becomes necessary to discharge the gases directionally or away from live circuits.

7. The proximity of grounded structures to the path of the discharge gases, which caused some concern before these tests were made, does not appear to be as serious as at first believed. During the tests a grounded metal plate was located 4 ft from the center discharge vent, and later at distances of 3 ft and 1½ ft, without causing circuit flashover or affecting the tube performance.

8. In the one test made on an expulsion protective gap mounted at a line tower, the short circuit cleared successfully, and without the discharge gases affecting any of the other phase wires of the circuit under test, or the phase wires of the other circuit which was alive and carrying load at the time. When the test circuit was cleared, after this test, the tube functioned again, indicating that the line switching surge had sufficient voltage to flash over the external gap in combination with the internal gaps. It is proposed to prevent this kind of abnormal operation by increasing the external gap, which can readily be done.

9. The maximum number of times any one tube interrupted short-circuit current on these tests was eleven. This under normal service conditions on a line, might correspond to a number of years of actual service. After the 11th test the tube was carefully examined and no visible deterioration was observed beyond a slight internal erosion. While no information is available as to the ultimate life of the tube in service, it appears at present that this feature will not retard the practical application of the tube for lightning protection.

10. If fast relays are employed, the relay time will have to be increased on circuits where expulsion protective gaps are employed to prevent the circuit relaying out. On this group of tests, relay targets (showing relay plungers had moved to a point sufficient to set the target) showed in 38 of the 41 tests. In 10 of the tests, the fast relays actually closed, tripping the circuit, although the short circuit had actually been cleared by the expulsion gap as evidenced by the oscillograms.

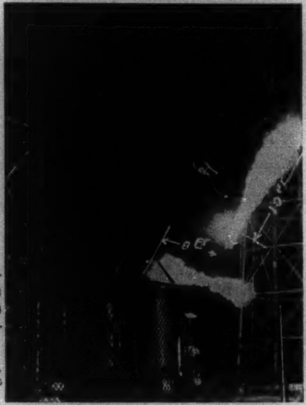

FIG. 6—EXPULSION PROTECTIVE GAP OPERATING IN INVERTED POSITION

76 kv to ground. 6,700 amp crest. Test No. 26

Typical tube operations at the time of tube functioning are shown in Figs. 5 and 6. The corresponding power currents interrupted are shown in Fig. 7, test Nos. 20 and 26.

Fig. 5 shows the expulsion gap with middle vents restricted by two 1-ft pipes and bottom vent restricted with a 90 degree elbow and a 1-ft pipe, successfully interrupting in 0.65 cycles 2,850 crest amperes (single-phase to ground) short-circuit current on the 132-kv system. A medium discharge is visible from the middle and bottom vents. The arc at the top of the tube is the power arc in the external gap. The record of short-circuit current on this test is shown in Fig. 7, test No. 20.

Fig. 6 shows the test of an expulsion gap without the restricting vents, breaking 6,700 crest amperes. The tube on this test has been mounted with the normally grounded discharge end on the line side (for convenience in measuring internal tube pressure). The conical discharge at the top, therefore, normally would discharge at the ground end, away from the insulator string where it would cause no hazard to insulator flashover. This picture, being taken at night, shows the discharge more plainly than the somewhat lighter discharge shown in Fig. 5. The oscillogram of current interrupted is shown in Fig. 7, test No. 26.

The expulsion gap was mounted on a tower, and successfully discharged a crest current of 5,900 amperes. The current record is shown in Fig. 7, test No. 41.

*Summary of Field Tests.* While this series of field tests on the expulsion protective gap was not extended to determine all the limiting factors and to just what extent they are involved in the design and performance of the tubes, sufficient data were obtained to indicate that the tube, in its present state of development for 132-kv lines, deserves serious consideration as a practical device in rendering a transmission line lightning proof.

## SERVICE EXPERIENCE

Much of the operation experience to date has been secured by the Arkansas Power & Light Company on 110-kv lines. Unfortunately few new lines have been constructed during the past three years, few improvements to existing construction have been undertaken and research has been correspondingly curtailed. The amount and range of experience data are, therefore, much more limited than normally would have been expected or should be available if the expulsion gap could have been adequately developed and its merits fully realized.

*Camden-Magnolia 110-Kv Line.* Probably the earliest installation of expulsion gaps (then called arc interrupters) was on the Camden-Magnolia 110-kv line of the Arkansas Power & Light Company.[1] These gaps were manufactured in the field by using blown expulsion fuse tubes. One end was closed by a metal cap and into the open end was inserted a wire electrode of such length that the internal gap in the tube was approximately 80 per cent of the length of the fiber. For the 69-kv tubes used on this 110-kv line the length of fiber is 44 in., length of internal gap 30 in., and bore 5/8 in.

The methods employed for mounting the expulsion gaps are illustrated by Figs. 8 and 9. On the two pole structures the gaps are clamped to a light channel by means of *U* bolts, the channel being grounded. The air gap between conductor clamp and end of the tube is 5 ft. The 7-ft crossarm and 12-ft section of pole are in series with the 6 insulator units. This arrangement does not provide a very great margin for lightning flashover by the expulsion gap route as compared with the insulator, crossarm and pole section,[2] however, it has functioned successfully since crossarms and poles have not been damaged.

On the 3 pole angle structures the expulsion gaps were placed in the protecting horn gaps which were installed on the poles with the original construction for protecting the long wood guy insulators. This method of mounting has the disadvantage that insulator flashover occurs, whereas it would be preferable for the flashes to be direct from the conductor to the ends of the tubes. Such a design would relatively be simple though usually it would be necessary to compensate for variations in the conductor position.

The operating results secured on this 28-mile line have been very illuminating as well as successful. Originally the drain points were spaced at about 2-mile intervals, part of them employing conventional expulsion fuses and part expulsion gaps. Several successful operations were recorded without corresponding line tripout. Flashovers phase-to-phase and to ground occurred between drain points though the full insulation in the poles and crossarms was utilized. In 1930 on the central 9-mile section of the line, all guys and drain points were removed in order to secure the maximum lightning insulation possible for making lightning voltage measurements.[1] On the two end sections the spacing of the expulsion gap installations was decreased to one mile, then to one-half mile in the same year. During the 2½ years since, the expulsion gaps on the protected sections are credited with 21 successful operations without line tripout and 2 failures to function have occurred.

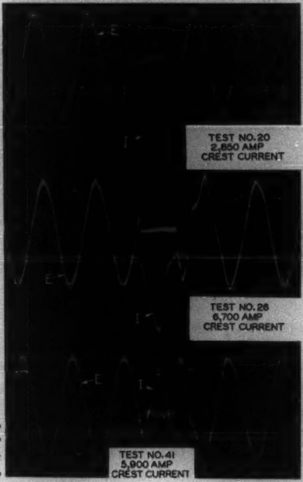

Fig. 7—Typical Oscillograms of Voltage (76-Kv Rms) and Current

*Waterville-Arlington 110-Kv Line.* The second experimental installation was in 1931 on a 10-mile section of a 50-mile line of the Tennessee Public Service Company. In the original construction of the line, 24-ft wood guy insulators were employed and pole protecting horns were installed on each structure. This extremely high lightning insulation has not been effective in reducing the number of flashovers[3] and the application of expulsion gaps indicates the greatest promise for effecting improvement. Expulsion gaps are installed on about every third structure as it had been learned from the experience of the Arkansas Power & Light Company as well as other observations, that on *H* frame wood construction, lightning can be expected to travel as much as 1,000 ft to 1,500 ft to discharge at relatively low insulation drain points rather than flashing the entire length of the pole and crossarm at intermediate structures. These installations are also similar to Figs. 8 and 9 except that on the two pole structures the gap in series with the expulsion gap is 2 ft instead of 5 ft. Also the pole grounding wire is extended as a bayonet above the poles to protect the crossarms and poles from direct strokes to the structure.

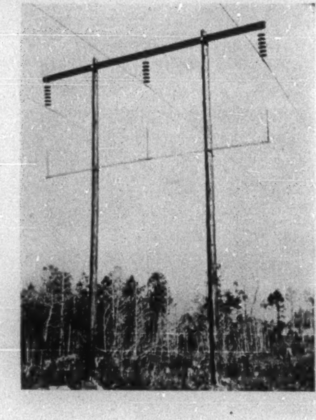

Fig. 8—115-Kv Expulsion Protective Gaps

Camden-Magnolia line. 5-ft series gaps

In the 1½ years 4 operations have been recorded only 1 of which is credited as being successful. In 3 cases tube failures occurred which were not entirely unexpected as the three-phase symmetrical short-circuit kva was approximately 500,000 kva and the tubes would probably be rated more nearly one-half of this value. However, the installation is experimental and that is one of the things desired to be learned. Grounding resistance values are high on this particular line, generally limiting the single phase-to-ground fault currents to a fraction of the phase faults. For successful application of expulsion gaps it, no doubt, will require a combination of high interrupting capacity phase gaps and low interrupting capacity grounding gaps as illustrated by Fig. 2B.

*Carpenter-Pine Bluff 110-Kv Line.* In October, 1931 the Carpenter-Pine Bluff 65-mile line of the Arkansas Power & Light Company was placed in service. In order to secure as positive a demonstration as practicable of the merits of the expulsion gap and drainage scheme, gaps were installed on every structure. One-half of the line employs series gaps of 5 ft and the 7 ft crossarm and pole section as illustrated by Fig. 8, the other half, a 2-ft series gap and the crossarm. The angle structures are similar to Fig. 9. Again the expulsion gaps were made up from conventional expulsion fuse tubes with the upper end capped and the electrode inserted into the open lower end.

The operation of this line has been quite successful. During one year the expulsion gaps have been credited with 10 successful operations and 4 failures. In three instances the tubes failed, either skyrocketing out of the *U* bolt clamps or bursting. In the fourth case a structure evidently was struck by lightning resulting in a flash along the crossarm.

The failure of the tubes was ascribed to insufficient interrupting capacity and to the obstruction to the opening by the lower electrodes, also to the paper wads used as operation indicators. The electrodes since have been replaced with smaller wire and cork indicators substituted. Since these changes no tripouts of the line due to lightning have been recorded in 7 months' operation though lightning storms over the line have occurred. However, an examination of the gap operation indicators had not been made.

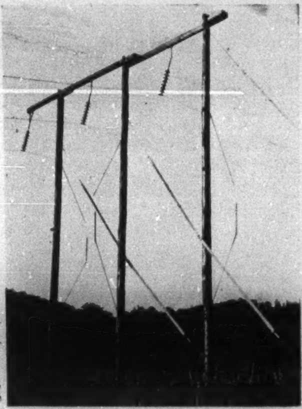

Fig. 9—115-Kv Expulsion Protective Gaps

Camden-Magnolia line. Angle structure

Further development of the device indicates that it would have been preferable to leave the lower end of the tube open and attach the long electrode to the cap as illustrated by Fig. 1. Another scheme being experimented with as an indicator is to bend a light lead strip across the open end of the tube.

*Pine Bluff-Little Rock 110-Kv Line.* Another 110-kv 45-mile line of the Arkansas Power & Light Company with expulsion gap installations at about one-half mile intervals has not performed as well as the two lines described. On this line failures of the tubes and their mountings have been more numerous. These also have been improved and better performance is indicated. Six tripouts occurred in about two-thirds of a lightning season, though about twice this many would be expected based upon the record for the line during previous years and other lines in 1932.

*13.8-Kv Installation.* Only a very limited application of expulsion gaps has been made as yet in the lower voltages. The possibilities for accomplishing improved line performance by the use of gaps is perhaps even greater in this class of construction than for the higher voltage transmission lines. Particularly is this the case since overhead ground wires are hardly applicable on account of the high lightning insulation and other features required for their successful operation. Fig. 10 illustrates a typical experimental 13.8-kv installation of the Dallas Power & Light Company. No operating experience had been secured at the time of preparing this paper, from this or the few other installations which were made in 1932.

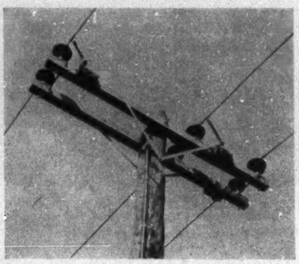

FIG. 10—13.8-KV EXPULSION PROTECTIVE GAPS

One inch series gap

### RESULTS

The results indicate very definitely that the expulsion gap properly developed and applied has great promise for minimizing line tripouts due to lightning. Particularly would they seem applicable on wood construction and on lines where conditions are not favorable to the functioning of overhead ground wires. Considerable improvement in performance is indicated on wood lines with expulsion gap installations spaced 2,000 ft to 3,000 ft, provided very high lightning insulation is maintained phase-to-ground and phase-to-phase at all intermediate structures. On steel or bonded and grounded hardware construction, gaps will be required at every structure to be effective. The insulations which can be protected should be about as shown by Table I. Reasonably accurate knowledge concerning minimum as well as maximum fault currents are essential and in many cases it may be necessary to use the multiplex scheme as illustrated by Fig. 2B.

Operation of the expulsion gaps is extremely rapid and with the application of high speed relays it will be necessary to introduce possibly 3 or 4 cycles to permit of gap operation without relay action.

Expulsion gaps as at present developed with their series air gaps are not generally applicable for the protection of conventional substation and apparatus insulations. It should be noted, however, that the magnitude of the lightning voltages transmitted to stations can be limited to rather low values, by the use of expulsion gaps.

During the experimental stages in the application of expulsion gaps some simple means for detecting operation of the tubes is advisable in order to secure dependable experience data. A flexible metal target is now available which gives an indication when the tube has functioned.

### ACKNOWLEDGMENTS

The authors acknowledge with thanks the cooperation and help furnished by the Operating Organization of the Appalachian Electric Power Company and the staff at Glen Lyn Plant during the field tests. It is also desired to thank Mr. R. R. Pittman of the Arkansas Power & Light Company for permission to use the results from his early and later experimental installations of expulsion gaps, also Mr. Chase Hutchinson of the Tennessee Public Service Company and Mr. H. K. Doyle of the Dallas Power & Light Company for data used in the preparation of this paper.

Thanks are also due to Mr. E. J. Wade of the General Electric Company for his assistance in securing data used in the paper.

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## Discussion

**L. V. Bewley:** This discussion is concerned primarily with the effect of tower footing resistance on the operation of the expulsion protective gap. These gaps have an upper and a lower current limit; in the present designs the span of these limits being from about 4:1 to 10:1. It is therefore essential to select gaps for a given system such that:

1. The maximum system short-circuit current is less than the upper limit of the gap, for if it exceeds this limit the gap is liable to burst.

2. The current permitted by the tower footing resistance is greater than the lower current limit, for if less than the minimum value the follow current will be insufficient to extinguish the arc, and a circuit interruption will result.

3. The number of gaps involved by a single lightning discharge shall be limited by the tower footing resistance so that the current per gap delivered by the faulted system will exceed the minimum current rating of the gap, and therefore extinguish the arc.

From the last two considerations it is seen that the tower footing resistances may play a vital part in the proper functioning of the expulsion gap, and they cannot be neglected; although it is by no means necessary to reduce them to the low values required for an effective ground wire installation.

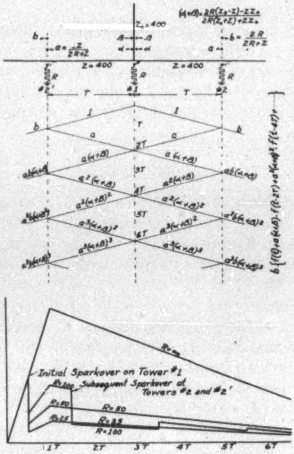

FIG. 1

In Fig. 1 there is shown the effect of tower footing resistances and subsequent gap sparkover in limiting the wave crest on a line equipped with expulsion gaps. The successive reflections that constitute these waves may be calculated by means of the lattice given at the top of the figure. It is evident that the gaps on adjacent towers will flash over in succession as long as the advancing wave crest exceeds their sparkover value. Therefore, in order to limit the number of gaps involved by a single lightning wave, the tower footing resistance must be kept within bounds, for otherwise the follow current per gap will not be sufficient to clear the arc. If the lightning bolt surge impedance is $Z_0$, the incident wave of the stroke is $e_0$ and the footing resistance $R$, then at the $n$th adjacent tower at which a gap flashover occurs the advancing wave crest is reduced to

$$V = b^n\,(RI) = \left(\frac{2R}{2R+Z}\right)^n \left(\frac{2ZRe_0}{Z_0Z + (2Z_0+Z)R}\right)$$

When this becomes less than the minimum voltage $V$ at which the gap will spark over with the type of wave involved, no more gaps will flash over. The total number of gaps involved (counting both ways from the stricken tower) is therefore $(2n+1)$.

The above equation has been plotted in Fig. 2. For example, in an extreme case if $e_0 = 10 \times 10^6$, $V = 1 \times 10^6$, and $R = 600$ ohms then 13 gaps will be involved. The number of gaps permitted to spark over for a given lightning stroke should be less than the ratio

$$\left(\frac{\text{maximum current rating of gap}}{\text{minimum current rating of gap}}\right)$$

In most practical cases not more than 3 adjacent gaps will be simultaneously involved.

In the neighborhood of the station it is advisable to reduce the tower footing resistances to very low values—of the order of a few ohms—for by so doing the duty on the station protective devices will be minimized.

**V. M. Montsinger:** The writer discusses the expulsion gap from the standpoint of coordination of station apparatus. It should be remembered that the expulsion protective gap is intended for the protection of line insulation against outages and not as a protective device to station apparatus. Even the coordination gap should not be looked upon as a protective device, because its impulse voltage level is not really low enough for this purpose. The real function of the coordination gap is to serve as the last line of defense in case the real protective device, like the lightning arrester or overhead ground wire, should permit a dangerous voltage to get by. Therefore, for the expulsion gap to serve as a protective device it must meet two requirements which up to the present time it does not appear to meet. First, it should be capable of keeping the incoming impulse voltage considerably below the coordination gap level, and second, it should be absolutely reliable and fixed in its flashover characteristics.

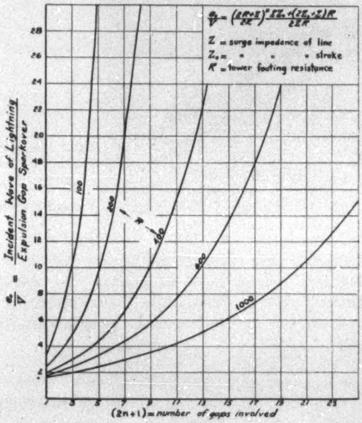

FIG. 2

With reference to its impulse level, referring to the right hand column in Table I, it will be found that the rod gap spacings protected by the expulsion gap are in every case higher than the coordination gaps recommended by the Transformer Subcommittee. The difference ranges from 6½ to 18 per cent, with an average of about 10 per cent.

With reference to its reliability, as pointed out in the paper, the present design of expulsion gap has several limitations. If the current is too large it blows up. After receiving a certain number of shots it wears out. There is no certainty then that it will maintain its original flashover characteristics.

Not realizing the limitations of these expulsion gaps someone may attempt to use them in establishing coordination of station apparatus. While it might be found possible to develop an expulsion gap of the same impulse level as the coordination gap yet until one can be worked out to the same degree of reliability and sturdiness as a rod gap or ring gap it would not be suitable to take the place of the coordination gap. Or, if the insulation level of the station apparatus should be higher than the standard level by 10 per cent or more, it may be proposed to use the expulsion gap as a coordination gap. Again, this is contingent on having a gap that will not change in its flashover values.

In summing up then, the expulsion gap can not be used either as a protective device to station apparatus or as a regular coordination gap.

**A. M. Opsahl:** Referring to Table I of the paper, the writer asks the authors what data were used in arriving at the maximum and minimum current rating. Were these tests made on a laboratory circuit where the current is limited very largely by reactance without any shunting resistance to stimulate the effect of a line? Do these current values give the maximum and the minimum symmetrical current values for which the equipment was adjusted or is the maximum value the full unsymmetrical value of current that the unit will interrupt?

It seems that there is an inconsistency in the table of insulation which the authors state the units will protect. For instance, in the 115-kv rating, a 35-inch rod gap and 7 of the 5¾ spaced suspension insulators can be protected. If negative impulses or surges are assumed these 2 will flash over at very much the same value. However, on positive surges, the 35-inch rod gap is equivalent to about 6 of the suspension insulators, or if 7 of the suspension insulators are required, it would be necessary to have approximately a 43-inch rod gap to give equivalent flashover. Is the suspension insulator string the measure of the flashover voltage of their protector or is the 35-inch rod gap the measure of the protection which the unit will afford on both positive and negative wave?

**Philip Sporn:** Since the largest number of line faults on modern high voltage lines are due to the effects of lightning, any means of reducing the duration of these faults to a time below that required for a circuit breaker to open will of necessity better line performance as it affects voltage conditions on the line, system stability, and uninterrupted service.

While laboratory and field tests on the expulsion protective gap have not been carried to the point of obtaining complete knowledge of the gap performance under all conditions, these tests do indicate that the gap is capable of supplying a very high degree of protection against line flashover and also a reliable means of interrupting fault currents on an actual power system, if properly applied. Whether the expulsion protective gap, as at present designed, will stand up in service when subjected to weathering and the elements can only be determined by experience.

The preliminary tests on the 132-kv expulsion protective gaps gave such promise that it was decided this year to make an experimental installation of these gaps on one of the lines of the American Gas and Electric Company. The 65-mile, 2-circuit, steel tower Glenlyn-Roanoke line was chosen for the installation. The gaps are being installed on all three phases of one circuit at each tower. This installation is now in progress; and it is expected it will be completed in time to obtain considerable experience with the gaps during the present lightning season.

The physical application of these expulsion protective gaps to all insulator assemblies of a 132-kv transmission line becomes a real problem. Reference to Fig. 3 of the authors' paper indicates (on the right-hand side of the illustration) the complications involved in mounting the gaps on all three phases of the one circuit. The actual structural details of the mounting, as well as alterations required in the tower structure become rather complicated. Besides the problem of complications involved in applying the protective gaps to the line, there is also the problem of keeping a tower structure clear and open for purposes of line inspection, maintenance, and repair. The cluttering up of a tower itself with additional structural members as well as the protective tube gap itself may well prove a hazard exceeded only by the hazard the installation of the tube is intended to remove. Considerable thought must, therefore, be given to the application of these expulsion protective gaps to a high voltage line.

A careful study of installation details was given, in considering the protective gaps for the Glenlyn-Roanoke line, with the result that a scheme was developed for mounting the gaps on the insulator hardware and assemblies, independent of any mechanical support direct to the tower structure. The advantages of mounting the expulsion protective gaps in this manner will be apparent to any one having any close connection with the operation and maintenance of transmission tower structures. Later on, an arrangement as shown in Fig. 3 (left-hand illustration) of the authors' paper was worked out.

In the actual field installation of expulsion protective gaps now being made on the Glenlyn-Roanoke 132-kv line, 3 methods of gap mounting are being used; first, the single angle mounting of the gap on the structure, second, the mounting of the gap on the insulator assembly, and third, a modification of this second design shown in Fig. 3 where the gap is mounted in 2 parts on the insulator assembly. The purpose of using all 3 methods of mounting the protective gaps was to determine, from the very start, the actual operating performance of the 3 types of mounting and their relative advantages and disadvantages.

The operation of this installation of 132-kv expulsion protective gaps on the Glenlyn-Roanoke line will carefully be watched not only from the point of view of the performance of the tube in protecting the line against lightning flashover and interrupting power current, but also the tube's ability to withstand weather, the elements, and the best way of mounting it. Successful operation of the expulsion protective gap in actual service over a period of time, will, it is believed, be a distinct step forward in applying practical lightning protection to high voltage lines, and particularly, to lines in heavy lightning territory or in territory of high ground resistance.

**L. L. Perry:** The service records of the 132-kv lines of the system as discussed by Mr. Sporn, show very clearly that lightning in some localities is a much greater hazard than in others. Hence, in the worst lightning territory, devices like those now on trial may prove to be decidedly economic, whereas the same devices may be elsewhere—say on the western mountain slopes of California, extravagant and hazardous.

**Howard S. Phelps:** Where the use of expulsion protective gaps is being considered serious attention must be given to the warning given in the paper where it is stated that "during the operation of the expulsion gap pressure is developed within the tube which, if too great, will burst the tube and if too small allows the power arc to continue." These limitations are especially important in the case of systems where different switching set-ups permit supplying energy to a given point from different sources or even the same source but over different routes. Obviously, under such conditions the short circuit kilovoltampere for a given set-up may exceed the capacity of the expulsion tubes while for a different set-up the short circuit kilavoltampere may be inadequate for proper functioning of the protective devices.

The estimate by the authors that the effectiveness of this scheme of protection probably is equal to that expected of the ground wire with low tower footing resistance provides a means by which one may compare costs of the two protective schemes in terms of effectiveness.

It will be interesting to learn what further operating experience discloses concerning this scheme of protection against lightning disturbances.

**K. B. McEachron:** The data given in Table I represent a composite of data taken both in the laboratory and in the field, which include the effect of the transmission line.

The maximum and minimum current values are based on the actual tube currents for which the expulsion protective gaps are designed.

Table I also shows the number of insulators and spacing of rod gap which can be protected by the expulsion gap of a given rating. Because a 115-kv tube can protect a 7-unit string and also a 35-in. rod, it does not necessarily follow that the 35-in. rod gap and the 7-unit string are equivalent. The volt-time curve for the expulsion gap is not the same as that of the rod gap or the insulator string and differences appear because of polarity. However, to avoid the necessity of specifying an exact wave and its polarity, the margin between the expulsion gaps and the flashover of insulator strings and rod gaps was made large enough to absorb the variations due to these factors. As a result an expulsion gap listed as protecting a 7-unit string may under some conditions protect a 6-unit string but not for all conditions. This method of expressing performance appears to be commendable on account of its simplicity.

# The Deion Flashover Protector
## and Its Application to Transmission Lines

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Associate, A.I.E.E. Associate, A.I.E.E.

***Synopsis.**—The deion flashover protector is a device intended for the protection of insulation such as used on transmission lines. In operation the lightning discharge passes through the device and the resulting power arc is extinguished without causing a system disturbance. Applications must be based on the surge flashover of the insulation to be protected, the system fault current, and the voltage at which that current must be interrupted.*

* * * * *

### GENERAL

On power transmission lines a flashover due to lightning usually results in a power arc and a line outage. The deion flashover protector provides a path for the spark where the resulting power arc can be extinguished.[1,2] Electrodes within a tube serve as spark and arc terminals. The walls of the tube are made of such material that the arc generates a gas which assists in extinguishing the arc. An external air gap usually is placed between the tube and the line.

This flashover protector can operate a number of times in succession without maintenance. A device requiring the renewal of a fuse would be inoperative in case of a repeated stroke. From photographs of lightning taken with a moving camera it would seem that multiple strokes within a second are quite possible.

### FLASHOVER CHARACTERISTICS OF PROTECTORS AND LINE INSULATION

The flashover protectors show a very short time lag of breakdown. When raising the surge voltage applied to the protector and its air gap by small increments, breakdown either does not occur at all or it occurs usually less than 4 microseconds. If a sufficient number of shots are taken in this narrow voltage range, some larger time lags may be observed. The curve in Fig. 1 shows the complete time-lag curve on a 1.5-40 microsecond wave. In the same figure are time lag curves of a pin insulator and a rod gap having the same minimum surge flashover. From these curves it could be assumed that with three such breakdown paths in parallel a lightning surge of the above length or shorter any discharge would take place through the protector as it takes a longer time for the spark to form around the insulator or in the rod gap. Practically it is difficult to maintain such a fine balance; so the protected insulation must have a higher minimum surge flashover than the protector with its external air gap.

If the pin of this insulator is supported on wood the surge flashover can be increased.[5,6] At best the flashover to ground is raised to that of the air gap between line and the nearest metallic object held at ground potential. To gain this increase in flashover, the wood arm or air gap clearances must not be bridged by metal crossarm braces, guy wires or other metallic fittings.

Increasing the surge flashover of a line by the use of wood will decrease outages but high surge voltages are found to split arms, pole and guys.[3,4] The flashover protector applied at any point will discharge these high surges, interrupt the power arc and prevent damage to that structure.

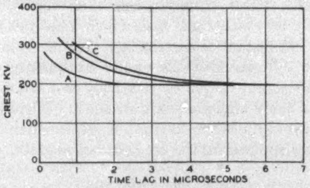

FIG. 1—TIME-LAG CHARACTERISTICS ON A 1.5-40 MICROSECOND WAVE

A. Deion flashover protector
B. Pin insulator
C. Rod gap

### POWER INTERRUPTION

The probability of a power arc forming in any path after a surge flashover seems to be a function of the length and surroundings of the path, the power circuit, the point on the power cycle at which the surge occurs and the duration of the surge current.[7,11] However, it is known that lightning flashovers have resulted in power arcs over most if not all of the present types of transmission line insulation. After a power arc has been established it may extinguish at the first current zero;

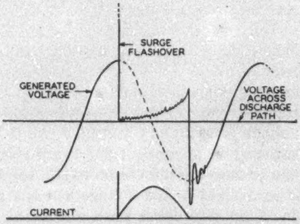

FIG. 2—VOLTAGE AND CURRENT RELATIONS DURING DISCHARGE OF A FLASHOVER PROTECTOR

assume as in Fig. 2 that the surge occurs at the crest of the power voltage. The first half cycle of current lags the generated voltage by 90 degrees as we assume that the current is limited by reactance alone. At the first current zero, if the arc is to extinguish, the arc gases must withstand the crest of generated voltage immediately, except as modified by the transient disturbance.

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1, 2. For references see bibliography.

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If a comparison be made between an arc in the open and an arc within gas forming walls of suitable dimensions it is found that the open arc length must be some twenty times as great in order to interrupt the same current at the same voltage. The reason for the better extinguishing characteristics of the enclosed arc is the turbulent mixing of the relatively cool and un-ionized gas from the walls of the enclosure with the arc gases.[8,9] This cool gas splits up the arc into many small filament-like arcs. These filaments are then surrounded by relatively un-ionized gas into which ions continuously diffuse. At instant of current zero the ions from the arc filament diffuses into the space surrounding it and forms a column of gas of relatively low ionic-density having a fairly high dielectric strength. When the rate of increase of dielectric strength is greater than the rate of voltage application the arc does not reignite.

## RECOVERY VOLTAGE[12,13]

Assume a single line-to-ground fault limited by transformer reactance as in Fig. 3. At current zero as in Fig. 2 the voltage attempts to rise immediately to the crest of line-to-ground generated voltage. Before this change in voltage can occur the electrostatic capacity of lines and equipment must be charged through the reactance of the system.

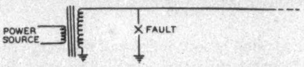

FIG. 3—CIRCUIT CONDITIONS UNDER WHICH A FLASHOVER PROTECTOR MUST INTERRUPT POWER CURRENT

The two extreme conditions are shown in Fig. 4. Where the line or lines are short and the transformer reactance high the recovery voltage appearing across the fault is equivalent to the voltage across a capacity charged through a reactance as in Fig. 4A. The recovery voltage is oscillatory and may rise to twice generated voltage plus an amount due to arc voltage. Where the line or lines are infinite in length, the recovery voltage is equivalent to the voltage across a resistor equal to line surge impedance when a constant voltage $E$ is applied through the transformer reactance as in Fig. 4B. Each overhead line has about 500 ohms surge impedance. Where lines are finite in length a reflection from the open end results in an overvoltage as in Fig. 4B. It is apparent that, due to the reflection the resultant voltage transient approaches the one analyzed in Fig. 4A. Both methods of analysis most obviously lead to the same result, and, for practical purposes it is in nearly all cases sufficient to calculate the rate of recovery assuming a lumped line capacity.

The theoretical maximum overvoltage due to oscillations is reduced usually by the damping of the system. Obviously the flashover protectors are connected always between a line and ground or line-to-line not in series with the line so that any benefit due to the reduction in rate of recovery voltage always is effective.

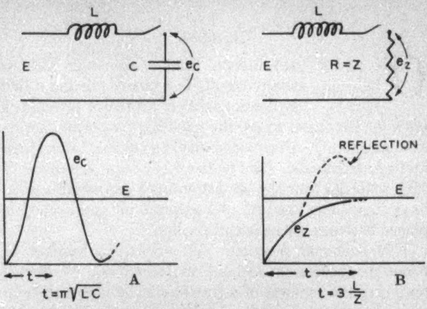

FIG. 4—(A)—EQUIVALENT RECOVERY VOLTAGE WITH A SHORT LINE CONNECTED TO THE TRANSFORMER

(B)—EQUIVALENT RECOVERY VOLTAGE WITH AN INFINITE LINE CONNECTED TO THE TRANSFORMER

Where the protectors are installed on a line it is not always possible to obtain a negligible ground resistance. The power current following the discharge of a single protector is limited by this resistance as well as the system reactance. The current being more nearly in phase with the voltage, the recovery voltage rises abruptly to something less than the crest of normal line-to-ground voltage. This is favorable. However, when two protectors connected to a common ground discharge simultaneously, the first unit to interrupt power current may be required to withstand power voltage equal to normal line-to-line not line-to-ground voltage even on a solidly-grounded neutral system.[14] This is true because the protector that still is carrying current causes

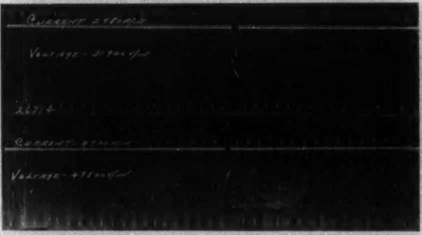

FIG. 5—POWER INTERRUPTION OSCILLOGRAMS OF A SYMMETRICAL CURRENT AND AN ALMOST COMPLETED UNSYMMETRICAL CURRENT

the ground electrode to rise in potential nearly to that of the lines still grounded, thus throwing full line-to-line potential across the protector that has just cleared. In applying these devices to low voltage lines with relatively high fault currents this fault resistance effect must be taken into account so that a properly rated unit will be applied.

In Fig. 5 are shown 2 oscillograms of current interruption at the first current zero. Although 1 current wave was displaced almost completely, the recovery voltage also was to the crest of line-to-ground voltage, not some lower value. This being the case it must be assumed that it is possible for the recovery voltage to rise abruptly to a value above line-to-ground voltage across the first of the two protectors to interrupt.

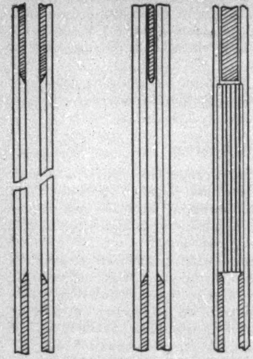

Fig. 6—Typical Section of Protector Construction

As a basis for rating, the protectors are tested for power interruption characteristic in the laboratory where the arc is started by a fine wire. The recovery voltage is very rapid as no line is connected. If tests are made with 500 ohms in parallel to simulate a line of infinite length the range in current that can be interrupted is increased or the power voltage rating is raised. Due to the variations in system conditions it is felt that this latter method of rating the units is unduly optimistic and will lead to misapplications.

### Mechanical Structure

The elements of the deion flashover protector are very simple. Two electrodes extend within a bone fiber tube assembly such that a surge voltage applied to either end will always result in a discharge within, not outside the tube. If the gases are vented only at one end a solid electrode is used at the other. High current tubes usually have a discharge path of circular section. Low current units have a discharge path of some form of slot.

The slot will interrupt a greater range in current as the arc will be in intimate contact with the fiber over a wide range in arc section. The arc in a round tube must begin to fill the bore of the tube before it is in equally intimate contact with the walls. Different typical designs of fiber structure and electrodes are shown in Fig. 6.

There is an air gap usually between the upper end of the protector unit and the line. This gap is of such a length that it will not discharge due to normal line-to-ground voltage. The mechanical support and arcing horn, if any, depend on the design of the structure supporting the line. Fig. 7 shows 3 units applied to a pole top switch.

### Operating Limits

To protect a given insulating structure against flashover a certain upper limit is set to the distance between inside electrodes. This limited internal gap determines the maximum power voltage this unit can clear after an operation, and also the range in power current that can be interrupted at that voltage.[2] Current limits are determined by the failure to interrupt or the bursting of the tube. Practically speaking, the higher voltage units require a ratio of about 3 to 1 in maximum to minimum fault current. This range can be increased where higher insulation permits a longer tube.

The protectors do not have a low enough discharge voltage to protect so-called normal station insulation. They are being used to protect in surge proof distribution transformers as these transformers have a very high ratio of impulse strength to operating voltage.

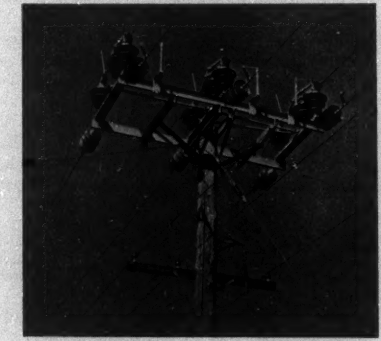

Fig. 7—Flashover Protectors Applied to a Pole Top Switch

Transmission lines will flash over unless protected adequately by ground wires.[15,16] It is estimated that unless the line-to-ground wire flashover distance is greater than 8 ft it is not possible to prevent side flashes from the ground wire to the line. This eliminates most low voltage lines from such protection. High voltage lines already built may not adequately be protected by ground wires due to weak towers, inadequate clearances, or high resistance grounding conditions. Lines that have reasonable insulation and fault circuit condition may be equipped with these protectors. Usually the difference between the flashover of the insulation and discharge voltage of the protector is small so that little protection is extended adjacent structures. Definite protection is afforded at the point of application; protection at a distance is a function of the surge front, distance, ground resistance and the difference between protector discharge voltage and insulation flashover.

Pole top switches, if operated open, cannot be improved greatly by over insulation to ground due to limited flash distance across the open switch. Therefore, they offer a good field of application for these devices.

### SERVICE APPLICATIONS

Although the protector is a relatively new device, it already has had considerable service to demonstrate its practicability. One of the first lines which was equipped with this device is a 110-kv wooden pole line and the protectors were placed at regular intervals. In this case they had several years of service and although called upon to operate many times they have had a perfect record. A more recent application was made on a steel line of 66 kv. This line is 50 miles in length. The majority of line insulators are equipped with protectors. Since this installation has been made no outages have resulted during lightning storms. In another 66-kv application a few of the units have failed mechanically. These units evidently cleared this circuit before failure and did no damage. In this case it was noted that operating conditions were more severe than estimated when the application was made. This illustrates the care that must be exercised in making applications. There have been other protector applications on 33-kv and 13.8-kv lines but the service in these instances has not been of sufficient length from which to draw definite conclusions.

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## Discussion

**R. E. Hellmund:** Lightning arresters have been available for quite some time and have been used largely to protect station and distribution equipment. However, while the lack of protection of the line as a whole resulted in outages, the cost of protecting the entire line by lightning arresters was not justified economically. The significance of the availability of such inexpensive devices as described in the paper, together with the more general application of surge-protected distribution transformers, is that all exposed parts of the system can now be economically protected against surges. This, in turn, will of course greatly decrease outages and increase service reliability.

It must be appreciated that there are limitations to the application of this device. For a given system voltage and power follow current at the point of application, there is a minimum surge flashover value for which the device can be designed, and to secure protection the flashover of the insulator string must be greater than this value. When these requirements are met for the higher operating voltages, the device is applicable only for line protection, and normally designed station equipment still must be protected by suitable lightning arresters.

It may be of interest to compare the trend of the developments along this line in this country with the entirely different means that have been employed in Europe to solve the same problem. There, in order to cope with the troubles caused by arcing to ground, etc., Petersen coils and other arc-suppressing arrangements were introduced to a great extent. Naturally, such possibilities were repeatedly considered in this country, but the application of these arc-suppressing coils was found difficult for various reasons and particularly on account of the greater complexity of the American systems and the consequent difficulty of properly tuning the coils. This, along with the great progress that has been made in this country in connection with arc-deionizing devices, makes it quite logical that a solution was reached along the lines indicated in the paper.

**K. B. McEachron:** The authors refer to the use of the protector for the protection of distribution transformers. While it is true that the distribution transformer does have a high ratio of impulse strength to operating voltage, yet it would seem that some form of arrester that holds the potential to 1/3 or 1/2 of that of the protector would be preferable on account of the additional factor of safety. It is well known that in service transformers may be subjected to conditions of operation which tend to decrease the strength of the insulation, indicating the desirability of as much margin between the protective level and the strength of the transformer as possible.

Nothing is stated in the paper concerning the operation of the protector on ungrounded circuits. It would be of interest to know what the authors would propose for the ungrounded circuit. This point comes up frequently not only in connection with the higher voltage circuits but in relation to distribution circuits also.

**Howard S. Phelps:** The discussion of the situation that exists upon interruption of power current by one of two protectors, connected to a common ground, which have functioned simultaneously emphasizes the care that must be exercised when selecting protectors for low voltage lines capable of delivering high values of fault current.

When more operating experience with deion flashover protectors has been acquired it is hoped the authors will make this information available to the Institute and thus amplify the very meager service information appearing in their paper.

**J. Slepian:** The origin of the deion flashover protector at the Westinghouse Company did not arise from any accidental discovery. Several years ago, Mr. Torok conceived his brilliant idea of combining the spark gap and expulsion fuse to make a device for protecting insulator strings from flashover due to lightning. The writer admired greatly his alertness in recognizing how the special properties of insulator strings and transmission lines and the then newly discovered facts and theory of the extinction of a-c arcs in self-generated gas blasts would fit together one with the other to permit the development of a new kind of protection against outages by lightning. The writer gave his enthusiastic encouragement, and is highly gratified that success has crowned Mr. Torok's work and that of his associates with a device that is so simple as to permit of almost universal application.

The special property of insulator strings used in the deion flashover protector is the high ratio of the impulse flashover voltage to the normal power voltage. If this ratio were much lower as in other apparatus it would be almost impossible to make a gap that will break down below the impulse flashover voltage, and yet interrupt an arc maintained by the power voltage.

The special properties of transmission lines made use of are the low ratio of the maximum short-circuit current to the minimum short-circuit current, and the influence of the distributed capacity of the line in slowing up the voltage recovery transient following a current zero. The influence of the latter property of the slow recovery characteristic in shortening the arc length required for a given power voltage is well known. But the former property also is very important for the extinction of an arc in a self-generated gas blast as in an expulsion fuse. The length of tube required for a given voltage is very largely dependent on this ratio. Roughly we may say that the cross-section of the tube is determined from mechanical considerations, by the maximum current that the tube must handle. With the given section, the length of tube required depends on the minimum current to be interrupted, increasing as this minimum current decreases, down to a certain small current, for less than which the needed length of tube does not need to increase. For a given maximum current, the length of tube needed to be capable of interrupting all currents down to zero is very much greater than that needed if the minimum current is a considerable fraction of the maximum current. With the shorter tube to interrupt the power current, it is much easier to make a gap that will break down at sufficiently low impulse voltages.

It may be seen, then, how the special properties of the protected and protecting device cooperate to give the extremely simple and practical deion flashover protector.

**J. J. Torok:** Mr. McEachron suggested that it would be desirable to reduce the protector breakdown potential to 1/3 or 1/2 of the present unit, so that old transformers could be protected against lightning surges. A number of tests run on transformers that have been in service for a number of years and have not been abused showed a very high impulse strength. Apparently aging had no effect on the insulation. Since the distribution transformer insulation is operated at a very low gradient its life is not reduced by the operating voltage and with normal attention the insulation should be good for the entire life of the transformer. The impulse strength of the transformer on which protectors are now used is several times the breakdown voltage of the protector. Should the effectiveness of the transformer insulation be reduced there still would be a margin between the breakdown voltage of the protector and that of the insulation.

Regarding ungrounded circuits where arcing grounds may be expected, the deion protectors used in transformers will operate very satisfactorily. The breakdown voltage of the deion gap is well above the voltage created by arcing grounds, so that there would be no tendency to set up a continuous arcing within the deion protector. The deion gaps also are so designed that they will interrupt very low current arcs. Thus even if the deion gap does operate, it will clear the circuit.

The application of deion gaps to high voltage ungrounded systems does present a number of difficulties; principally that of a very wide range of currents to be interrupted. In the case of a single line-to-ground operation the current to be interrupted merely is the charging current of the system. However, if the fault should be a double line-to-ground, the line-to-line currents relatively would be very high. To take care of this condition we have proposed a scheme similar to that shown in Fig. 2B of Mr. McEachron's paper. Three tubes designed for heavy currents are used to take care of the line-to-line faults, while a fourth designed for low currents is inserted in the grounding lead.

# Design Features of the Port Washington Power Plant

BY G. G. POST*

Fellow, A.I.E.E.

***Synopsis.***—*This paper presents an analytical discussion of some of the important decisions reached in the design of the new Port Washington power plant. The initial section of the station will have a capacity of 80,000 kw and will utilize 1,230 lb steam pressure and 825 deg F steam temperature at the throttle and 825 deg F steam temperature at the reheat point.*

*Summaries of certain economic studies, which formed the bases for decisions, are included, but no statistical information on the various pieces of equipment.*

* * * * *

## GENERAL

THE Port Washington generating station of The Milwaukee Electric Railway and Light Company, now under construction, is located on the west shore of Lake Michigan at East Port Washington, Wisconsin, 28 miles north of Milwaukee. The station's initial capacity will be 80,000 kw (one unit) with a possible ultimate capacity of 400,000 kw (five units). The outstanding feature will be its unit design, that is, there will be a single boiler for each single turbine generator and also one set of transformers, one 132-kv transmission line, and one set of auxiliaries for each unit.

Fundamentally, Port Washington's design is based on that of the Lakeside plant except that such advancements are incorporated as are justified by operating experience and improvements in the power plant art. The principal advancement, aside from the unit arrangement which has been mentioned, is the adoption of 825 deg F temperature for both throttle and reheat.

## SELECTION OF SITE

Load growth made it apparent in 1928 that generating capacity would have to be added to the Wisconsin-Michigan system of the North American Company in order to maintain the proper relation between system capacity, peak demand, and reserve capacity. With by far the major portion of the system's generating capacity concentrated at one point, Lakeside, south of Milwaukee, it was deemed advisable not to put "all the eggs into one basket" by further expansion of Lakeside, whose capacity had reached 310,800 kw, but to locate a new plant at a point north of Milwaukee which would permit feeding energy into the Milwaukee district from two almost diametrically opposite and widely separated sources. (See Fig. 1.)

In the case of power plants in the Milwaukee area, water-borne coal has a distinct advantage over all-rail coal from the same field in the eastern district. This is caused by the decided and abrupt railroad rate increase on coal in passing through the Chicago district. In fact, the increase is so large that even mid-western coal (Indiana and Illinois), which must of necessity pass through Chicago, cannot compete with the eastern coal when the latter is shipped by water. The comparisons given assume the various coals on an equal Btu basis. This point is mentioned to bring out the importance of needing to select a site where coal can be received by water.

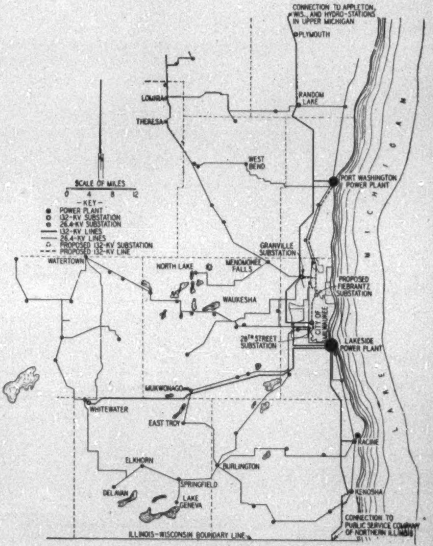
CONNECTION TO APPLETON, WIS., AND HYDRO-STATIONS IN UPPER MICHIGAN
PLYMOUTH
LOMIRA
THERESA
RANDOM LAKE
WEST BEND
PORT WASHINGTON POWER PLANT
SCALE OF MILES
0
4
8
12
-KEY-
POWER PLANT
132-KV SUBSTATION
26.4-KV SUBSTATION
132-KV LINES
26.4-KV LINES
PROPOSED 132-KV SUBSTATION
PROPOSED 132-KV LINE
WATERTOWN
NORTH LAKE
MENOMONEE FALLS
GRANVILLE SUBSTATION
PROPOSED FIEBRANTZ SUBSTATION
WAUKESHA
CITY OF MILWAUKEE
28TH STREET SUBSTATION
LAKESIDE POWER PLANT
MUKWONAGO
WHITEWATER
EAST TROY
RACINE
ELKHORN
BURLINGTON
SPRINGFIELD
DELAVAN
LAKE GENEVA
KENOSHA
CONNECTION TO PUBLIC SERVICE COMPANY OF NORTHERN ILLINOIS
ILLINOIS-WISCONSIN BOUNDARY LINE
LAKE MICHIGAN

FIG. 1—PORT WASHINGTON IS LOCATED TO THE NORTH OF THE MILWAUKEE METROPOLITAN AREA

It serves as a second source of supply, widely separated from Lakeside which is to the south. Continuity of service will thus better be insured

The selection of a site, therefore, resolved itself into a search for one which would most nearly fulfill the following requirements:

1. Be north of the Milwaukee metropolitan area better to insure continuity of service. (Lakeside is south.)

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*Vice President in Charge of Power, The Milwaukee Elec. Rlwy. and Light Co., Milwaukee, Wisconsin.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

2. Be located as close to the load center as practicable.

3. Be adjacent to Lake Michigan where the condensing water supply is ample and cold.

4. Be at a location where harbor facilities for lake boats have been established or could be provided at reasonable cost.

5. Be at a location to which large industries might be attracted so that these could be served with energy directly from the station bus bars.

6. Be located so that connections to railroad lines (preferably the company's own) could readily be made.

Port Washington was the only place that met satisfactorily all of these requirements. In addition, if in the future, combination of coal prices and freight rates should become such as to give rail-borne coal an advantage over water-borne coal, the change to rail-borne coal could be made at Port Washington without any difficulty whatever.

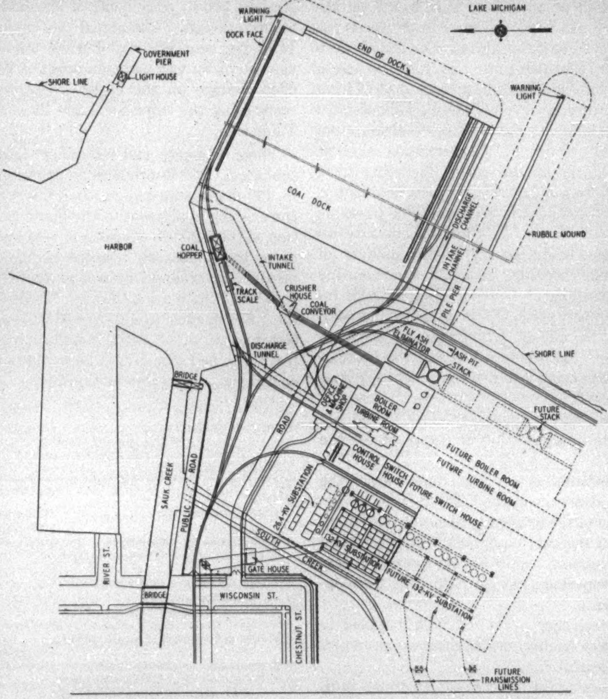
WARNING LIGHT
DOCK FACE
LAKE MICHIGAN
GOVERNMENT PIER
SHORE LINE
LIGHT HOUSE
END OF DOCK
WARNING LIGHT
COAL DOCK
DISCHARGE CHANNEL
RUBBLE MOUND
HARBOR
COAL HOPPER
INTAKE TUNNEL
INTAKE CHANNEL
TRACK SCALE
CRUSHER HOUSE
COAL CONVEYOR
PILE PIER
FLY ASH ELIMINATOR
ASH PIT
STACK
SHORE LINE
DISCHARGE TUNNEL
BRIDGE
OFFICE & MACHINE SHOP
BOILER ROOM
TURBINE ROOM
FUTURE STACK
ROAD
CONTROL HOUSE
SWITCH HOUSE
FUTURE BOILER ROOM
FUTURE TURBINE ROOM
FUTURE SWITCH HOUSE
SAUK CREEK
PUBLIC ROAD
28.4-KV SUBSTATION
SOUTH CREEK
132-KV SUBSTATION
FUTURE 132-KV SUBSTATION
RIVER ST.
GATE HOUSE
BRIDGE
WISCONSIN ST.
CHESTNUT ST.
FUTURE TRANSMISSION LINES

Fig. 2—The Port Washington Power Plant is Situated Conveniently for Condensing Water, Coal Handling, and Transmission Line Facilities

**Its unit design permits flexibility in adopting different forms of generating equipment for future extensions**

Although Lakeside burns water-borne coal it has not a dock of its own. Its coal is received over the docks of Milwaukee coal companies and from there hauled to the plant by rail. Port Washington, on the other hand, will have a coal dock which will eliminate the intervening rail haul with its attendant costs. The effect of this will be to lower its fuel cost about $2.59 per hundred million Btu below that of the Lakeside plant.

## Determination of Size

In determining the size of the plant and of the units desire to make it possible to cooperate with industrial concerns that might wish to locate in the vicinity of the plant was an important factor. Because of its harbor, dock, and railroad facilities, Port Washington offers to new industries advantages far superior to those that can be found anywhere else in the vicinity of Milwaukee. Because of this it was felt that it would not be beyond reason to contemplate the possibility of industrial development in the vicinity of the plant to the extent of about 150,000 kw.

The load growth on the system in 1928, when Port Washington was originally planned, amounted to 37,000 kw over the year previous, with prospective increases for 1929 and 1930 of 40-000 kw each. For the latter two years provisions were made for adding 75,000 kw to Lakeside's capacity. Increases of 40,000 kw each for two years succeeding 1930 were not then unreasonable.

The fact that Lakeside's last two additions were of 75,000 kw capacity each, that normal load had been increasing at the rate of nearly 40,000 kw per year, and that there was a possibility of a large industrial load in addition to the normal growth, prompted the decision to install 80,000 kw initially at the new station.

## Mercury-Steam Cycle Consideration

The possibility of large industrial plants locating in close proximity to the power station, some of which might require large amounts of process steam in addition to their electrical demands, suggested that serious consideration be given the mercury-steam cycle. For a given process steam demand the mercury cycle can generate over twice as much by-product electrical energy as can a straight steam cycle, or conversely, the net heat consumption in Btu per switchboard kilowatt-hour would be considerably less with the mercury cycle than with a straight steam cycle if the kilowatt-hour outputs were the same. On the basis of straight condensing plants of equal capacity (100,000 kw) it was found that the mercury-steam cycle in order to equal the 1,200-lb steam cycle in total annual costs would have to be operated at an annual load factor on the plant of at least 65 per cent. At lower load factors the 1,200-lb steam cycle showed a saving. For the particular project under consideration, the 1,200-lb steam cycle showed a saving in investment costs of $18.74 per kilowatt while the mercury cycle showed a gain of 2,550 Btu per kilowatt-hour in station heat consumption. With coal at $3.80 per ton and fixed charges taken at 13 per cent the total annual costs (including fixed charges) would be the same at 63½ per cent load factor, while with coal at $3.60 per ton they would be the same at 67 per cent load factor. In these calculations allowances have been made for the smaller amount of auxiliary power and the lower capacity of condensing water and coal handling and preparation facilities required by the mercury cycle. It is obvious that with lower coal costs the money saving due to saving a certain quantity of coal becomes less and the installation of the more expensive mercury equipment becomes more difficult to justify.

It was concluded that the mercury cycle should not be adopted for the initial section of the plant for the following reasons.

1. Because of the small net savings, if any, which the mercury cycle could show over the 1,200-lb cycle,
2. Because some of the untried portions of the fundamental parts in the mercury equipment might cause an outage when the capacity could not be spared for any appreciable time especially not for correcting developmental defects, and
3. Because the mercury cycle could be installed in succeeding units very readily, should these experimental matters prove successful.

At the time of making the mercury-steam study, indications of future price trends both of fuel and construction materials were taken into consideration. Recent trends have been along the lines assumed and have not altered the conclusions reached.

## Selection of 1,200-Lb Steam Cycle

As has been stated, the design for the Port Washington plant has as its underlying basis the design and operating experiences of the Lakeside plant. Lakeside's first 1,300-lb boiler was placed in operation in October 1926. In October 1929, its second high-pressure boiler went into service. By the time that a decision on the pressure for the Port Washington plant had to be made, 3½ years of operating experience had been had with the Lakeside equipment. The availability factor for the last 2 of these 3½ years on high-pressure boilers was 84.3 per cent and 88.5 per cent, respectively. (Incidentally, it might be interesting to record at this point that during 1932 the availability for the 4 high-pressure boilers at Lakeside averaged 93.7 per cent.) A careful analysis of the operating statistics for 1929, the last full year before making decisions for Port Washington, showed that Lakeside's high-pressure system had in that year effected an actual net saving of $58,965 over straight 300-lb equipment of the latest and the most modern design. The actual fuel saving resulting from 14.12 per cent less coal burned amounted to $89,365 against which was made an offset of $30,400 for annual fixed charges on the larger investment; maintenance costs being the same for 1,200 lb as for 300 lb. (See Table I.)

These economy and reliability figures definitely established 1,200-lb pressure as being far superior to 300 lb, 300-lb pressure being used in this comparison because the existing equipment in the plant, before the installation of the 1,200-lb equipment, was built for it. But in order to exhaust all possible claims for intermediate pressures, a comparison was made between 600 lb and 1,200 lb. The results, shown in Table II, indicated that the 1,200-lb cycle would save $36,754 annually over the 600-lb cycle in the initial installation at Port Washington, after deductions had been made for fixed charges on the greater investment required.

TABLE I—COMPARISON OF ACTUAL 1,200-LB GENERATION WITH 300-LB GENERATION
LAKESIDE—1929

| | | |
|---|---|---|
| *Economy* | | |
| 1. Station generation | Million kwhr | 993.9 |
| 2. Station output | Million kwhr | 948.7 |
| 3. Generation by 1,200-lb cycle | Million kwhr | 236.0 |
| 4. Per cent of generation by 1,200-lb cycle | | 23.8 |
| 5. Overall station heat consumption at Lakeside | Btu per kwhr net | 14,882 |
| 6. Heat consumption of an all 300-lb plant | Btu per kwhr net | 15,400 |
| 7. Heat consumption of an all 1,200-lb plant | Btu per kwhr net | 13,225 |
| 8. Heat saving on 1,200-lb generation | Btu per kwhr net | 2,175 |
| 9. Per cent saving of 1,200 lb over a new 300-lb plant = item 8 divided by item 6 | | 14.12 |
| 10. Total 100 million Btu saved = item 3 times item 8 divided by 100,000,000 | | 5,133 |
| 11. Cost of fuel per 100 million Btu | | $17.41 |
| 12. Total saving for 1929, 1,200 lb over 300 lb | | $ 89,365 |
| *Investments* | | |
| 13. Greater investment cost of 1,200-lb equipment over 300 lb (per unit) | | $200,000* |
| 14. Greater annual fixed charges at 13 per cent | | $ 30,400 |
| *Net Saving* | | |
| 15. Net saving for 1929, 1,200-lb cycle over new 300-lb cycle | | $ 58,965 |

Actual operating statistics showed that Lakeside's 1,200-lb cycle had saved 14.12 per cent in coal over that which would have been burned had 300-lb equipment been installed. Maintenance costs were no higher and, except for slightly higher fixed charges, the fuel savings indicate the net savings.

*Second unit started in commercial operation November 1, 1929.

TABLE II—COMPARISON OF 1,200-LB GENERATION WITH 600-LB GENERATION
(Reheating to Same Temperature for Both Pressures)
ESTIMATED FOR PORT WASHINGTON

| | | |
|---|---|---|
| *Economy* | | |
| 1. Estimated annual generation for initial installation 80,000 kw at 60 per cent annual load factor | Million kwhr | 421 |
| 2. Saving in heat consumption by 1,200-lb cycle over 600 lb (average all loads) | Btu per kwhr | 856 |
| 3. Annual Btu saving in favor of 1,200 lb | 100 million Btu per year | 3,610 |
| 4. Cost of fuel per 100 million Btu | | $14.82 |
| 5. Total annual fuel saving, 1,200 lb over 600 lb | | $ 53,500 |
| *Investments* | | |
| 6. Greater investment for 1,200-lb boiler room equipment | | $147,168 |
| 7. Greater investment for 1,200-lb turbine room | | $ 19,300 |
| 8. Lesser investment for 1,200-lb turbine room equipment | | $ 20,000 |
| 9. Lesser investment for 1,200-lb station tunnels, circulating water system, and coal handling system | | $ 17,650 |
| 10. Net greater investment for 1,200-lb installation | | $128,818 |
| 11. Annual fixed charges on greater 1,200-lb investment at 13 per cent | | $ 16,746 |
| *Net Saving* | | |
| 12. Net annual saving of 1,200-lb installation over 600-lb installation of 80,000-kw capacity | | $ 36,754 |

In comparing the economies of 1,200-lb generation with 600 lb, a considerable saving in fuel was found. This, together with the unexcelled reliability record of Lakeside's 1,200-lb equipment decided the issue in favor of 1,200 lb.

Consideration of the possibilities of the Benson cycle showed that it held no inducements at this time. Efficiency gains from going beyond 1,200 lb were found to be slight because of rapidly increasing feed pumping costs and steadily decreasing energy gains.

The savings shown in Tables I and II, together with satisfactory overall operating experiences at Lakeside, were sufficient to warrant the adoption of 1,200 lb for Port Washington.

### SELECTION OF 850 DEG F (MAXIMUM) STEAM TEMPERATURE

Lakeside has a reputation for being a pioneering station in economically sound adventures. Thanks to a liberal company policy, marked by keen foresight, every opportunity has been given to improve the art of producing and distributing electrical energy. In planning Port Washington this same policy was continued. It was believed that progress should be made and that some improvements over Lakeside were possible. Among those considered was the possibility of going to a higher steam temperature. Superheater manufacturers, valve, pipe, and also turbine makers were consulted. All expressed their willingness to cooperate and subsequently quoted prices on equipment necessary not only to produce 825 deg F at the turbine throttle and reheat point, but to maintain it continuously: 850 deg F was specified as the maximum. The increase of 75 deg F in actual operating temperature (Lakeside's is 750 deg F) brings the total steam temperature up to the point where ordinary steels cannot be used in the turbine. Alloys require greater investment particularly in large turbines where they had not been previously applied to the extent that they had been in steam superheating equipment and in valves. The net greater cost of 850 deg F equipment totaled $28,170 in investment. With fixed charges taken at 13 per cent, the annual rate amounted to $3,650. The fuel saving on the other hand amounted to $18,720 per year, resulting from a 2.5 per cent better station heat consumption rate. The net saving was, therefore, calculated to be $15,070 per year. The greater investment resulted from a more expensive turbine, greater cost of valves and fittings, and greater cost of superheaters and reheaters. These greater costs were offset by investment savings in boiler plant equipment due to the smaller amount of steam required, less water storage required in steam drums, and by deferred expenditure for replacing the last row of turbine blades due to less moisture in the exhaust steam. (See Table III.)

TABLE III—COMPARISON OF 825 DEG F AND 750 DEG F TEMPERATURE AT BOTH THROTTLE AND REHEAT
ESTIMATED FOR PORT WASHINGTON

| | | |
|---|---|---|
| *Economy* | | |
| 1. Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor | Million kwhr | 421 |
| 2. Saving in heat consumption, 825 deg over 750 deg | Btu per sw. bd. kwhr | 300 |
| 3. Annual Btu saving, 825 deg over 750 deg | 100 million Btu | 1,263 |
| 4. Cost of fuel per 100 million Btu | | $14.82 |
| 5. Total annual fuel saving, 825 deg over 750 deg | | $ 18,720 |
| *Investments* | | |
| 6. Investment saving of 825 deg due to lower heat consumption | % | 2.5 |
| 7. Unit investment to which heat saving applies | $ per kw | 47.30 |
| 8. Total investment saving of 825 deg = $47.30 times 80,000 times 2.5 per cent | | $ 94,600 |
| 9. Total investment saving assuming 75 per cent of total saved | | $ 71,000 |
| 10. Additional investment saving in two steam drums, due to lesser storage required | | $ 5,670 |
| 11. Additional investment saving due to deferring replacing last rows of blades because of lesser moisture in exhaust | | $ 10,920 |
| 12. Total investment saving, 825 deg over 750 deg | | $ 87,590 |
| 13. Greater investment cost of 825-deg turbine | | $ 89,000 |
| 14. Greater investment cost of 825-deg valves and fittings | | $ 8,000 |
| 15. Greater investment cost of 825-deg superheater and reheater | | $ 18,760 |
| 16. Total greater investment cost, 825 deg over 750 deg | | $115,760 |
| 17. Net greater investment cost, 825 deg over 750 deg (item 16 minus item 12) | | $ 28,170 |
| *Net Saving* | | |
| 18. Annual fuel saving, 825 deg over 750 deg | | $ 18,720 |
| 19. Annual fixed charges on greater investment at 13 per cent | | $ 3,650 |
| 20. Net annual saving, 825 deg over 750 deg | | $ 15,070 |

An increase in operating temperature to 825 deg F from 750 deg F for both throttle and reheat showed a 2.5 per cent improvement in station performance. When the saving was capitalized on the basis of reducing equipment costs in the boiler room, it offset the increased cost of the turbine, valves and fittings and showed a substantial net saving for the higher temperature.

A higher steam temperature than 825 deg F at the turbine throttle with no reheat was considered purely experimental because it involved untried alloys. Creep in metals is hardly a consideration at 825 deg F, but at 1,000 deg F or thereabouts, it is extremely important. A throttle temperature of 825 deg F with reheat at the same temperature is a reliable, non-base-load combination, one that is made particularly attractive through the application of radiant superheating and reheating surfaces in the same furnace.

Lakeside's operating experiences with reheat are positive proof that variable loads are easily and safely carried. Reheat introduces minimum complications into the cycle.

## One Turbine, One Generator, and One Boiler

A previous study had shown that one large turbine generator would save $7.15 per kilowatt over two half size units in investment costs (turbine generators, foundations, turbine room building, electrical equipment, and switch house) and about $25,000 per year in operating costs due to a better rate of heat consumption. These savings were considered sufficient to warrant the installation of an 80,000-kw unit rather than two 40,000-kw units. Incidentally, an 80,000-kw machine would match almost exactly the 90,000-kva transmission lines which had been adopted for the Milwaukee district.[1]

Most of the original 1,200-lb installations in this country consist of 1,200-lb non-condensing turbines superimposed on existing 300-lb stations. In such installations, of course, new full capacity 1,200-lb boilers were required but the turbines were of comparatively small generating capacity. The economy of such an installation, due to having to maintain a practically constant pressure at the exhaust of the high pressure turbine for all loads, drops off rapidly in going from full load to partial load. Multiple-valve admission to the high-pressure turbine has been used as a partial means of overcoming this difficulty, but the process effects a saving in the high-pressure turbine only, whereas the largest part of the loss occurs at the exhaust of this turbine.

If the exhaust pressure is permitted to vary according to load through the use of so-called compound operation, savings of considerable magnitude can be made. Such operation naturally would have to be followed in a station which had boilers generating steam at but one pressure. The high-pressure turbine could, however, still remain segregated from the low through the adoption of a cross-compound machine. There then would be two separate turbines each with its own generator, a combination which has the advantage of keeping the low-pressure turbine in service when trouble is encountered in the high-pressure turbine. Should the low pressure section be forced from service at any time, the entire unit would be down and because of this fact a reserve equal to the capacity of the whole unit must be kept available at all times. The ability to operate the low-pressure section at times of high-pressure turbine outage, therefore, loses much of its significance. Besides, the reserve capacity in most cases can be operated at an economy very close to that of the low-pressure section alone. The advantages of tandem-compounding on the other hand are such as to win approval; they are, net investment savings of $1.12 per kilowatt resulting from (1) a lower cost of the turbo generator itself, (2) fewer electrical connections because of having only one generator, (3) less building volume, and (4) a credit for a smaller turbine room crane because of a narrower turbine room.

Many of the arguments presented against the cross compound unit apply to the steeple-compound unit also, although the economic advantage of the tandem over the steeple is not as great as it is over the cross compound. Inconvenience in operation and maintenance were also factors in deciding against the steeple-compound unit.

After having established the size and type of the turbine to be installed, the next consideration was the number, size, and type of boilers. Detailed comparisons were made on the installation of two boilers of small size (345,000 lb per hour capacity) and of one boiler of large size (690,000 lb per hour capacity).

One boiler was selected rather than two, because:

1. An investment saving of approximately $250,000 could be made.
2. The operation would be simpler due to not having to apportion the exhaust steam from the high-pressure section of the turbine to each of the two reheaters.
3. The presence of an 80,000-kw turbine generator on the system would require 80,000-kw reserve in any event. Therefore, no additional losses in capacity would occur due to boiler outage.

At Lakeside, three-drum bent-tube type boilers with comparatively large low-heat release furnaces had unprecedented reliability records. Certainly records of this nature could not be ignored in making selections for the Port Washington boilers. This fact notwithstanding, all arguments for the single-drum straight-tube boiler and high-heat release furnace were obtained and carefully weighed. Prices were secured and tentative layouts prepared so that an unbiased opinion as to their merits might be formed.

Exponents of the straight-tube boiler design with its complementary equipment maintained that with it a better proportioning of all of the heat reclaiming surfaces could be secured together with a lower overall investment cost. The use of less of the comparatively high cost boiler surface and more of the less expensive

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1. See paper on *The 60-Cycle Primary Transmission System of The Milwaukee Electric Railway and Light Company and Associated Companies in Wisconsin and Upper Michigan*, by C. D. Brown and E. W. Hatz, presented at the Great Lakes District Meeting of the A.I.E.E. at Milwaukee, Wisconsin, March 16, 1932.

economizer surface formed the basis for their arguments. They also maintained that less building volume would be needed. Contrary to expectations, the latter was not found to be true for Port Washington conditions, principally because of a 10-ft higher building which would be required. It was true, however, that a small saving in investment was shown with the straight-tube boiler layout over that of the bent-tube type but this saving was more than offset by operating losses. Table IV summarizes these gains and losses. Then too, high-pressure economizers (1,600 lb) which are an essential part of the straight-tube boiler layout were considered a potential source of trouble. As explained later, economizers were eliminated entirely from the Port Washington design.

It was concluded finally to adopt the bent-tube type boiler fired from one side only with a low-heat release hopper-bottom furnace beneath it. Besides the economic gains and the possibility of eliminating economizers, the following additional reasons influenced its selection:

1. About 50 per cent more water storage space is available which is very important when only a few minutes total storage is available.
2. Tubes being nearly vertical permit rapid water circulation which eliminates wide variations in drum-water levels throughout the load range.
3. Dry steam is obtained since the rear drum acts as a dry drum, it having little steam released from the water it contains.
4. Water wall connections can easily be made because of accessibility of the drums.
5. Suspended solids in the boiler water are removed effectively in the lower drum.

TABLE IV—COMPARISON OF BOILER DESIGNS FOR PORT WASHINGTON—INITIAL INSTALLATION

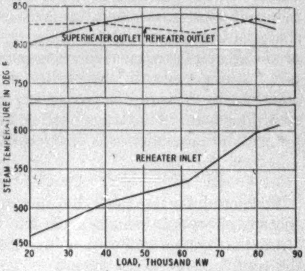
| | Bent-tube boiler low-heat release furnace | Straight-tube boiler high-heat release furnace |
|---|---|---|
| 1. Total investments in boiler, furnace, superheater, reheater, economizer, air-heater feeders, burners, and milling equipment* | $937,137 | $838,805 |
| 2. Greater investment of bent-tube boiler | 98,332 | |
| 3. Greater annual fixed charges at 13 per cent | 12,783 | |
| 4. Increased operating costs | | |
| a. Greater pressure drop in superheater | | $ 156 |
| b. Greater pressure drop in reheater | | 1,920 |
| c. Loss of heat in molten ash | | 1,780 |
| d. Lower overall boiler efficiency | | 6,370 |
| e. Poorer availability | | 3,900 |
| f. Lower reheat temperature | | 2,720 |
| g. Greater furnace maintenance cost | | 5,700 |
| h. Total greater operating costs | | $ 22,546 |
| 5. Net annual saving of bent-tube boiler with low-heat release furnace | $ 9,763 | |

The bent-tube boiler with a low-heat release furnace not only will produce an annual saving of $9,763 but will also permit the use of radiant superheat and reheat surfaces within the furnace, and afford other operating advantages.

*Building not included because costs would be identical.

### FURNACE

The slag-tap furnace, which was given some consideration, is a high-heat release furnace of relatively small size because the temperature in the furnace must be kept sufficiently high to maintain the ash in a molten state. The small size and high temperature preclude the use of radiant superheaters and reheaters. The latter are desirable because their inherent characteristics are such as to give automatically the most economical operating conditions at all loads. Superheaters and reheaters of the all-convection type give decidedly variable steam outlet temperatures with variations in load on the boiler necessitating desuperheating at the higher loads. This was considered objectionable because of the general unreliability of the desuperheating process. No desuperheater is required with the radiant surfaces in the Port Washington station design. On the other hand, large furnaces with a low rate of heat release (15,000 Btu per cubic foot per hour, maximum) are conducive to low maintenance costs and high availability. With steel walls, consisting of steam and water cooled surfaces on all 6 sides, there can be no wall erosion. Radiant superheater and reheater surfaces for side and rear walls and water tubes for the front wall and the ash screen were the final answer to the furnace problem after all advantages and disadvantages of other combinations had been carefully balanced.



CURVE 1

Uniform steam outlet temperatures such as these, from both the combination radiant and convection superheater and the radiant reheater, over a load range from full to quarter will tend to produce high overall plant efficiency

### RADIANT SUPERHEATER AND REHEATER

Selection of radiant heat absorbing surfaces for superheater and reheater rather than all-convection surfaces was prompted by economic considerations as well as the adaptability of these surfaces to the low-heat release furnace mentioned in the previous paragraph. More uniform steam temperatures over wide load ranges can be obtained automatically and thus the overall station economy can be improved. This is particularly true at low loads when all other factors in the system are working toward poorer economy. By virtue of the higher superheat the turbine efficiency is maintained higher than it would otherwise be at the lower loads.

The superheater selected has a radiant section and a convection section. The steam will pass first through the former and then the latter. With this combination the steam temperature to the turbine throttle will vary only from 830 deg F at full load to 802 at quarter load. The reheater on the other hand is radiant entirely and its outlet temperature will vary from 834 at full load to 827 at quarter load.

## AIR HEATER AND ECONOMIZER CONSIDERATIONS

Economizer and air heater surfaces—all waste heat reclaiming surfaces for that matter—are closely related to the type of cycle adopted for the station. In the case of Port Washington, a tentative cycle was decided upon at the time of placing the turbine contract. This called for the use of extraction heaters at 5 points. A comparison between 4 extraction heaters plus an economizer-air heater combination, and 5 extraction heaters plus an air heater only, indicated that a net annual saving of $7,429 could be made through the use of the latter. The major portion of this saving is effected by the 1.3 per cent better heat rate of the turbine due to the fifth heater. Although the addition of an economizer would reduce the flue gas temperature 25 deg F and thus make a substantial saving in boiler efficiency, the fixed charges on the greater investment for the economizer and piping (after taking credit for the smaller air heater) and the maintenance costs on the economizer would more than offset this gain. Five-stage heating with an air-heater but with no economizer was therefore decided upon.

## BIN AND FEEDER *vs.* UNIT SYSTEM

In determining the method of firing to be adopted, a thorough investigation was made into the adaptability of the unit system and of the bin and feeder system to the contemplated plant layout. The results showed that the boiler efficiency obtainable with the unit system was about equal to that of the bin and feeder system with no gain for either on such items as carbon loss, uniform grinding, etc. There were, however, inherent advantages of the bin and feeder system which influence total station economy rather than only boiler efficiency and it was these which decided the matter in its favor. The most outstanding of these advantages are:

1. Greater reliability. With the unit system any outage of a mill for any reason will cause a reduction in capacity of the boiler or complete outage of the boiler. Whenever a reduction in load occurs, it must be picked up by some standby or less efficient station, and a loss of 0.1 per cent in economy might result.

2. Flexibility. The low rating limitation of the unit mill is absent entirely from the bin system. This is particularly important at times of starting when low furnace temperatures are desired to prevent damaging superheater tubes.

3. Mill drying with flue gas can be used in the storage system to advantage, while on the other hand it cannot be used efficiently in the unit system. Venting flue gases back into the furnace is not conducive to efficient combustion and to the maintaining of proper flame control. With flue gas drying in a storage mill, 6 per cent of the total flue gas discharges to the stacks at a temperature 200 deg F lower than the usual exit temperature. In addition, air heater performance is improved due to the greater mean temperature difference and the lesser heat absorption in the air heater. After the flue gas mill drying system has been charged with the small coal vent loss, it shows a net gain of 0.5 per cent over using hot air and venting to the furnace.

4. Coal feed can be regulated more closely with the storage system resulting in the maintenance of high average $CO_2$ and fine control of excess air. With radiant superheaters and reheaters this is important. Coal feed variations of 10 per cent as are common with the unit system without hand adjustment can cause a 50 deg variation in reheat temperature and 0.6 per cent decrease in station economy.

5. Coal feed control at Lakeside where the storage system is used has been found to be so regular that boiler pressure can be regulated to within 5 lb of a standard. With the unit system, the pressure variations might be on the order of 50 lb. The difference of 45 lb in pressure at the turbine could cause 0.6 per cent difference in economy.

6. When using air drying with unit mills the heated air to the mill must be tempered with room air. This reduces the amount of air to be taken through the air

TABLE V—COMPARISON BETWEEN 4 EXTRACTION HEATERS PLUS ECONOMIZER-AIR HEATER COMBINATION AND 5 EXTRACTION HEATERS PLUS AIR HEATER ONLY
Four Extraction Heaters Plus Air-Heater Only Is Used As The Basis For This Comparison
ESTIMATED FOR PORT WASHINGTON

| | Gain | Loss |
|---|---|---|
| *Four-Stage Heating and Economizer* | | |
| 1. Saving due to lowering of flue gas by 25 deg F | $4,520 | |
| 2. Maintenance cost on economizer | | $2,000 |
| 3. Pumping cost for pressure drop through economizer | | 120 |
| 4. Fixed charges on greater investment cost for economizer and piping after deducting credit for smaller air heater, $35,800 at 13 per cent | | 4,654 |
| 5. Total costs | $4,520 | $6,774 |
| 6. Net annual loss for economizer | | 2,254 |
| *Five-Stage Heating* | | |
| 7. Better heat consumption rate due to fifth-stage heaters—112 Btu per kwhr | $6,995 | |
| 8. Maintenance cost on fifth-stage heaters | | 400 |
| 9. Pumping cost for pressure drop through heaters | | 120 |
| 10. Fixed charges on investment in fifth-stage heaters, also necessary piping, $10,015 at 13 per cent | | 1,300 |
| 11. Total costs | $6,995 | $1,820 |
| 12. Net annual gain for fifth-stage extraction heaters | 5,175 | |
| *Net Comparison* | | |
| 13. Net gain due to fifth-stage heaters | $5,175 | |
| 14. Net loss due to economizer | 2,254 | |
| 15. Net annual difference in favor of fifth-stage heaters | $7,429 | |

Economizers ordinarily are thought of as equipment used to enhance power plant operating efficiency. This tabulation shows that extraction heaters do this more effectively, and with far less need for worry about operating difficulties under the higher pressures encountered.

heater and reduces the boiler efficiency about 0.3 per cent below that of a storage system boiler where flue gas drying is used.

7. Automatic combustion control is much more positive on a storage fired boiler than on a unit fired one. With the latter, difficulties are encountered in coordinating the mill speed, primary air volume, and sizing of the pulverized coal particles with the requirements of the boiler. Lower overall efficiencies will result.

These advantages, totaling 2.1 per cent in station economy, can be credited to the storage system. Investment costs were found to be 74c. per kilowatt lower for the unit system. Labor, maintenance, and power were slightly in favor of the unit system. An important point in favor of the storage system is that most of its motors can be shut down at the time of the station peak. The unit system on the other hand requires peak electrical demand for auxiliaries coincident with the peak station demand and to provide the same margin in capacity an equivalent in generating capacity must be installed at the same station or elsewhere.

TABLE VI—COMPARISON OF STORAGE SYSTEM AND UNIT SYSTEM OF PULVERIZED FUEL FIRING—ESTIMATED FOR PORT WASHINGTON

| | | |
|---|---|---|
| *Economy* | | |
| 1. Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor | Million kwhr | 421 |
| 2. Saving in heat consumption, storage over unit | % | 2.1 |
| 3. Btu saving, storage over unit | Btu per kwhr | 252 |
| 4. Annual Btu saving, storage over unit | 100 million per year | 1,061 |
| 5. Cost of fuel per 100 million Btu | | $14.82 |
| 6. Total annual fuel saving, storage over unit | | $15,750 |
| *Labor, Maintenance and Power* | | |
| 7. Greater cost of labor (1 extra man) storage over unit | | $ 2,400 |
| 8. Greater cost of maintenance, storage over unit | | $ 950 |
| 9. Lesser cost of power, storage over unit | | $ 575 |
| 10. Net greater operating costs, storage over unit | | $ 2,775 |
| *Investments* | | |
| 11. Greater investment cost in mills, feeders, burners, motors, starters, duct work, foundations, air compressors, fuel bins, etc., storage over unit | | $59,112 |
| 12. Greater annual fixed charges at 13 per cent, storage over unit | | $ 7,685 |
| *Station Peak Capacity* | | |
| 13. Greater kilowatt demand of unit system motors at time of station peak | | 592 |
| 14. Value of 592-kw station capacity at $75 per kilowatt | | $44,400 |
| 15. Lesser annual fixed charges on station capacity, storage over unit | | $ 5,772 |
| *Net Saving* | | |
| 16. Net annual saving, storage system over unit system (item 6 minus item 10 minus item 12 plus item 15) = | | $11,062 |

The battle of storage *vs.* unit system of pulverized fuel firing was waged for many weeks in The Milwaukee Electric Railway and Light Company's engineering department before the storage system was awarded the decision. Its merits include not only an annual saving of $11,062, but greater reliability and flexibility, as well as safety, due to the possibility of using flue gas mill drying with it.

Another important advantage of the storage system is the safety to personnel and equipment occasioned through the use of flue gas for mill drying. A 12 per cent volume of $CO_2$ (an inert gas) is maintained in the mill system and collectors, so that danger of fire or of an explosion from smoldering coal is lessened materially.

The analysis, of which Table VI is a summary, showed the bin and feeder system to effect a net annual saving of $11,062 and this, together with certain operating advantages, formed the basis for its adoption.

### EXTRACTION HEATERS AND FEED PUMPS

After having determined the number of extraction heaters to be used in the heat cycle, a very important decision had to be made in regard to the location of the boiler feed pumps in the cycle. The high pressure boiler feed pumps at Lakeside, although they had been operating continuously for over four years and had never been the cause of 1,200-lb equipment outage, had demanded considerable attention and were creating maintenance costs which were considered too high. Their operation as a whole was rather delicate. An investigation showed the cause of the difficulties to be fluctations in feed water temperatures which set up uneven expansion and contraction in the various component parts of the pumps causing clearance variations, packing leaks, etc. The maximum feed water temperature delivered to the Lakeside 1,600-lb pressure pumps is 360 deg F while it might go down to 300 deg F or slightly below at light loads. The pumps at Port Washington, if they are placed on the discharge side of the extraction heaters, would be required to handle water to as high as 432 deg F temperature at full load and as low as 290 deg F at quarter load, a condition much more severe than that at Lakeside. Should they be located after the second heater, however, and made to discharge through the heaters at the remaining 3 extraction points, the temperature of the water entering the pumps could be held constant at 200 deg F. The manufacturers of the feed pumps were in hearty approval of the suggestion that the lower temperature be used in spite of the relatively low delivery pressure to the suction of the pumps, and promptly quoted on pumps with efficiency guarantees somewhat improved over those at Lakeside. This improvement in efficiency is incidental to the improved reliability of the pumps and to the 12 per cent saving in pumping energy occasioned by the lower specific volume of 200 deg F feed water compared with that of 400 deg F feed water. The somewhat higher cost for the high-pressure extraction heaters over the lower pressure type was not nearly enough to offset the advantages mentioned.

Two sets of high-pressure extraction heaters will be used, one on each of the feed lines to the boiler. Each feed line will have a separate high-pressure pump with a spare pump so connected that it can be substituted in either line. Two feed lines to the boiler will be used because better parallel operation of centrifugal feed pumps can be obtained when discharging through heaters and piping before pressures are equalized. Then, too, it was found economical to use two sets of heaters because by-passes around the heaters with their expensive fittings could be eliminated.

Interesting design details entailed in the construction of the high-pressure extraction heaters are worthy of mention because they have heretofore never been attempted. It is common knowledge that bolted heads with gaskets and stay-bolts are a serious problem in the use of high-pressure heaters. These have been entirely eliminated through the adoption of a head made from a solid forging bored out and supplied with an internal head cover, similar to a boiler manhole plate design.

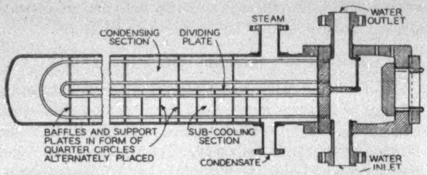

STEAM
WATER OUTLET
CONDENSING SECTION
DIVIDING PLATE
BAFFLES AND SUPPORT PLATES IN FORM OF QUARTER CIRCLES ALTERNATELY PLACED
SUB-COOLING SECTION
CONDENSATE
WATER INLET

Fig. 3—Extraction Heaters Built for 1,600-Lb Water Pressure Presented an Operating Problem Until This Design With Its Elimination of Bolted Heads With Gaskets and Stay-Bolts was Adopted

Steel tubes with *U*-bends have been decided upon because experience at Lakeside has proved them to be more reliable than brass tubes and they cost less. Corrosion of the tubes can be prevented entirely by complete de-aeration which is essential in any event in a 1,200-lb pressure plant.

Flash losses between the high-pressure heaters will be eliminated by cooling the drains in the lower sections of the heaters before cascading them into the next lower heaters. Separate drain pumps on individual high pressure heaters would be impractical because of having to pump against 1,300-lb boiler pressure. Calculations show an improvement of about ¾ per cent in plant economy through the elimination of flash losses.

### Generation at 22,000 Volts

In selecting the generator voltage, the following were considered:

1. No pioneering in generator voltages was desired.

2. A voltage was desired that would enable industries which might locate in the vicinity of the plant to connect their lines to the bus bars as economically as possible.

3. If any economies could be effected in the plant investment and operating costs by using a voltage higher than 13,800 (the Lakeside voltage) such economies should be realized.

4. It would be desirable to adopt a voltage which would permit the connection of the existing 26,400-volt secondary transmission lines of the company with a minimum of expense. This is not a matter of much importance because very little of the energy will be delivered at this voltage. Most of it will be stepped up directly to 132 kv.

5. A voltage was desired that all manufacturers would be willing to use in their machines without resorting to special construction, such as concentric conductors.

The voltage which most nearly met all of these conditions was found to be 22,000 volts. In using this voltage it was found that a saving of 0.3 per cent could be realized in investment and operating costs of generators and electrical equipment over similar costs for 13,800 volts. No saving could be effected by adopting 26,400 volts because equipment in the 34,500-volt class, which is more expensive, would then have been necessary. Because of the adoption of 22,000 volts, it is necessary to use auto transformers to connect to the lines operating at 26,400 volts.

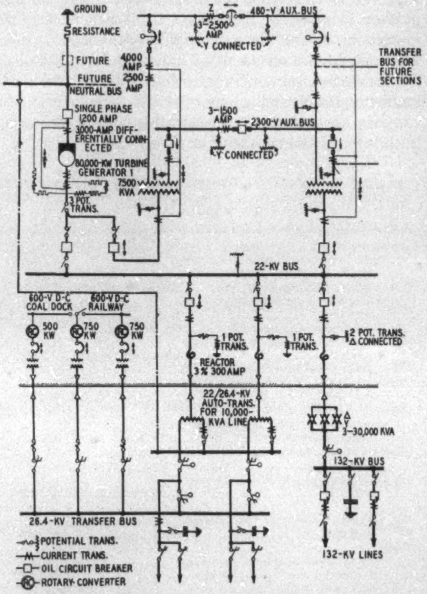

GROUND
RESISTANCE
FUTURE
FUTURE
NEUTRAL BUS
4000 AMP
2500 AMP
SINGLE PHASE 1200 AMP
3000-AMP DIFFERENTIALLY CONNECTED
80,000-KW TURBINE GENERATOR 1
7500 KVA
3 POT. TRANS.
Z
480-V AUX. BUS
3-2500 AMP
Y CONNECTED
TRANSFER BUS FOR FUTURE SECTIONS
3-1500 AMP
2300-V AUX. BUS
Y CONNECTED
22-KV BUS
600-V D-C COAL DOCK
600-V D-C RAILWAY
500 KW
750 KW
750 KW
1 POT. TRANS.
1 POT. TRANS.
2 POT. TRANS. Δ CONNECTED
REACTOR 3% 300 AMP
22/26.4-KV AUTO-TRANS. FOR 10,000-KVA LINE
Δ Y
3-30,000 KVA
132-KV BUS
26.4-KV TRANSFER BUS
POTENTIAL TRANS.
CURRENT TRANS.
OIL CIRCUIT BREAKER
RC ROTARY CONVERTER
132-KV LINES

Fig. 4—One Line Diagram of Port Washington Power Plant—Initial Installation

The rotary converters will be located in the basement of the control building and will supply service to the coal dock and to the Company's interurban railway system. One rotary converter is a spare and can be used either on the railway service or on the coal dock service.

### 22,000-Volt Indoor Switching Equipment

Whether to build a switch house and install indoor 22,000-volt switching equipment or to install metal clad equipment outdoors was given a great deal of consideration. Regardless of the decision on this point, it was recognized that it would be necessary to build a transformer repair house and control house which limited the decision simply to the switching equipment itself, main bus bars, reactors, etc. All of the comparative estimates made included the control house and transformer repair building. Estimates were obtained from the manufacturers on various kinds of switching equipment and it was assumed in the case of the outdoor metal clad equipment that there would be a likelihood of a reduction in cost of about 10 per cent during the time that the station was growing from its initial to its ultimate size. It was found that for the initial section the outdoor metal clad equipment would require an expenditure of $6.03 per kilowatt while the vertical indoor isolated phase construction, including building and foundations, would require an expenditure of $5.62 per kilowatt, or $0.41 per kilowatt in favor of the indoor vertical isolated phase arrangement. In the ultimate station, with relatively more switching equipment because of the duplication of switches on certain lines and the use of a ring 22,000-volt bus with reactors, the corresponding figures would be $7.62 per kilowatt for the outdoor metal clad and $5.78 per kilowatt for the indoor vertical isolated phase arrangement, including building, a saving in favor of the indoor arrangement of $1.84 per kilowatt. In view of the economies that could be effected and other advantages, such as the greater ease of making changes from the original layout and the use of oil-less circuit breakers in the indoor arrangement, it was decided to put all of the 22,000-volt switching equipment indoors. After deciding upon the use of indoor equipment, it was thought desirable to consider the merits of various kinds of indoor equipment and so cost figures were prepared on indoor three-pole assembly metal inclosed equipment. It was found that in the initial installation the metal inclosed equipment would cost $0.17 per kilowatt more than the vertical-isolated phase arrangement and $0.31 per kilowatt more in the ultimate installation. Vertical-isolated phase construction was therefore selected.

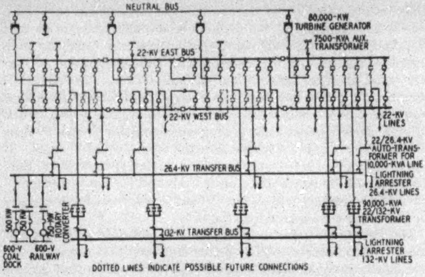

NEUTRAL BUS
80,000-KW TURBINE GENERATOR
7500-KVA AUX. TRANSFORMER
22-KV EAST BUS
22-KV WEST BUS
22-KV LINES
22/26.4-KV AUTO-TRANSFORMER FOR 10,000-KVA LINE
26.4-KV TRANSFER BUS
LIGHTNING ARRESTER
26.4-KV LINES
500 KW
750 KW
750 KW
ROTARY CONVERTER
90,000-KVA 22/132-KV TRANSFORMER
132-KV TRANSFER BUS
LIGHTNING ARRESTER
132-KV LINES
600-V COAL DOCK
600-V RAILWAY
DOTTED LINES INDICATE POSSIBLE FUTURE CONNECTIONS

FIG. 5—WIRING DIAGRAM

Showing main electrical connections when the Port Washington Power Plant has reached a capacity of 320,000 kw (4-80,000-kw turbine generators)

## AUXILIARY POWER SUPPLY SYSTEM

Alternating current auxiliary service will be provided by 7,500-kva three-winding transformers stepping down from 22,000 volts to 2,300 and 480 volts. There will be one transformer connected directly to the leads of each generator and one spare transformer connected to the 22,000-volt bus. Each transformer will supply auxiliaries for its own unit with automatic provisions for transferring the load instantaneously to the spare transformer in case of trouble on the normal supply.

Motors of 100 hp capacity and larger will be supplied at 2,300 volts and motors of less than 100 hp at 480 volts.

Direct current service supplied from motor-generator sets with a battery floated across the busses will be used to supply pulverized coal feeders, electrically operated valves, turbine room cranes, elevators, emergency lights, and magnetic pulleys.

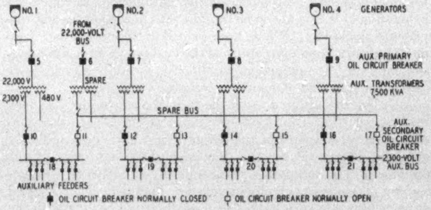

NO. 1
NO. 2
NO. 3
NO. 4
GENERATORS
FROM 22,000-VOLT BUS
5
6
7
8
9
AUX PRIMARY OIL CIRCUIT BREAKER
22,000 V
SPARE
2300 V
480 V
AUX. TRANSFORMERS 7,500 KVA
SPARE BUS
10
11
12
13
14
15
16
17
AUX. SECONDARY OIL CIRCUIT BREAKER
18
19
20
21
2300-VOLT AUX. BUS
AUXILIARY FEEDERS
OIL CIRCUIT BREAKER NORMALLY CLOSED
OIL CIRCUIT BREAKER NORMALLY OPEN

FIG. 6—SINGLE LINE WIRING DIAGRAM OF PRINCIPAL AUXILIARY CONNECTIONS

Oil circuit breakers 11, 13, 15, and 17 normally open. All other breakers normally closed. Should trouble develop between breakers 5 and 10 these breakers will open through the operation of differential relays. The opening of 10 causes 11 to close thereby maintaining service on all auxiliaries of generator 1. If the trouble is between 11 and 18, 18 opens through the operation of an overload relay leaving half of the auxiliaries operating; if between 10 and 18, 5 opens on overload and the opening of 5 in turn opens 18 and closes 11 thereby maintaining service on half of the auxiliaries. Whenever breaker 5 opens, the 480-volt service also is transferred to the spare. The 480-volt auxiliary connections are similar to the 2,300-volt connections and are relayed in the same way except for one minor difference not mentioned here

The only steam-driven auxiliaries in the plant will be 1 emergency feed water pump and 1 emergency house service water pump.

## CONCLUSION

The author wishes to emphasize that the comparisons presented in this paper and the conclusions reached apply to Port Washington conditions. Under other conditions, decisions might have been different.

It is hoped that the information presented in this paper will convey a general impression of certain trends in power plant design as interpreted by the engineers of The Milwaukee Electric Railway and Light Company.

The author wishes to acknowledge the valuable assistance in the preparation of this paper of F. L. Dornbrook, Chief Engineer of Power Plants, William E. Gundlach, Chief Electrical Engineer, C. F. John, Assistant to Vice President, and others of the engineering staff of The Milwaukee Electric Railway and Light Company.

## Discussion

**Alex D. Bailey:** While Mr. Post's paper possibly affords opportunity for discussion regarding certain detailed features of station design, it is important primarily because it embodies the best thought in station design, though it originated 4 or 5 years ago. The design of this station shows quite conclusively the value of simplification, which offers the greatest opportunity for reduction in investment cost. With the improvement which has been made in the reliability of both steam generating and turbine equipment in the last few years, the single unit type of station is rapidly gaining favor.

So far as the 1,200-lb turbine units are concerned, the performance record of all turbines for 1932 shows that the 1,200-lb units are fully as reliable as those operating at lower pressures. The 4 high pressure units at Lakeside have a particularly good record as all 4 of them are better than the average.

In the controversial question of the unit system versus bin system, the design apparently was based largely on reliability, which naturally appeals to all operating men.

**E. J. Billings:** Speaking abstractly from the standpoint of the manufacturer of power station equipment, a customer's evaluation of bids is apt to be fraught with uncertainties and surprises to the bidder. When, as presented in this paper, the customer fearlessly gives out details of the evaluation for a secondary evaluation by the engineering public, it is certainly a progressive step in the direction of equitable evaluation of bids.

Although the author stresses the point that the design has been worked out strictly for local conditions and that for other conditions or other locations the design might have been radically different, there still remains the possibility that some of the premises will be accepted more literally by a portion of the engineering public than is really intended or justified. This is stated in particular reference to that part of the paper dealing with the boiler and combustion equipment. To illustrate:

In Table IV the definite and unquestionable fixed charge item on the added cost of the bent tube boiler with large furnace is shown to be more than offset by a series of operating credits any one of which is subject to a variety of conflicting opinions. Suppose, for example, that the radiant superheaters and reheaters did not work out quite as anticipated, and instead of having a furnace maintenance credit over the high heat release slag tap furnace of $5,700 per year the situation was reversed exactly and the credit became a debit. Or suppose, for the same reason, the credit of $3,900 per year for better furnace availability became a debit instead. Thus, the margin of $9,763 per year over and above the fixed charge debit of $12,783 and in favor of the bent tube boiler with large furnace might work out to be something entirely different even to the point of changing the economics of the design selected.

When an engineering evaluation brings two quite radically different designs so close together in worth to the company that the difference is measured, as in this case, in terms of the order of 1 per cent of the annual fixed and operating charges, then the designer might well make his selection purely on the basis of which design he thinks will give him, his management, and his operators the greatest amount of satisfaction during the life of the equipment.

If more power station designers would present as freely as has the author of this paper their line of reasoning for evaluation by the engineering public it would do much to stabilize features of design on which there is now a considerable divergence of opinion.

**A. G. Christie:** Milwaukee's power plants from old Oneida Street to Lakeside have all been noted for their contributions towards advancing the art of steam station design and operation. The new Port Washington Station adheres to this tradition and Mr. Post's excellent paper will be studied in detail by power plant designers and operators. One is impressed with the painstaking consideration given to all equipment and particularly by the complete dollar analysis applied to each decision. This is good engineering, for little should be left to pure opinion or personal preferences unless these actually are justified by the economics of the case.

The decision to install 1 boiler per turbine is justified fully by the operating experiences of many plants. The writer has been an advocate of this system for years. The size of the units at Port Washington and the high pressure and temperatures employed are the outstanding characteristics of this 1 boiler per turbine plant.

In selecting boiler pressures, the engineers of this plant had the advantage of complete records of the 1,200-lb plant at Lakeside Station. In view of the excellent performance at this plant, one is not surprised at the decision to use this pressure at Port Washington, particularly when the various cost analyses indicated savings from the 1,200-lb plant. However, these savings are based upon 60 per cent load factor. One may question this assumption, for in the past, the average load factors of station equipment over their whole useful life falls greatly below this figure. It is evident that a long operating life is assumed as indicated by a rate of 13 per cent for annual fixed charges. If Port Washington is to be the base load station of the system, then Lakeside will be relegated to peak loads and its fine performance records accordingly will suffer. What is the basis for the selection of 60 per cent annual load factor?

Mr. Post takes pains to justify the use of 825 deg F steam and reheat temperatures. The writer believes that even higher temperatures could be fully justified. It is certain that special metals will be used for 825 deg F and the additional cost of materials for 25 to 50 deg F higher temperatures should not have been very great while the performances of the station would have been improved. One may expect stations operating at 1,000 deg F within a few years.

In view of the increasing use of slag bottom furnaces with high rates of heat release, the decision to use dry bottom furnaces with a heat release of only 15,000 Btu per cu ft will arouse much comment. Operating records of other stations with moderate rates of heat release such as Lakeside, Avon Beach, and Ashtabula, show low maintenance and high efficiency. The decision to retain this construction at Port Washington appears to be conservative.

The choice of the bin and feeder systems in place of the unit system also is contrary to present trends. This paper affords an opportunity to the advocates of the two systems to discuss thoroughly their merits and disadvantages in the light of recent operating results.

The selection of bent tube boilers with 5 stages of bleeding and air preheaters continues Lakeside practice. From theoretical considerations, this is the proper arrangement of heat recovery apparatus in spite of the increasing use of high pressure economizers.

Other writers have pointed out the savings in power to the boiler feed pump that may be secured by pumping cold rather than hot water. The Port Washington plant probably is the first to apply this idea in practice. This leads to the use of 3 bleeder heaters under full 1,600-lb boiler feed pressure and their performance will be followed with interest. In designing these heaters as shown in Fig. 3 a new idea of sub-cooling the condensate is introduced which Mr. Post claims will improve plant economy by ¾ per cent. One is led to question why advantage has not been taken of providing more counter-current flow at the steam entrance to take advantage of the superheat in the steam at certain of the upper heaters, to lessen or possibly overcome entirely the terminal difference of the leaving feed water.

While many savings are given in the paper, the writer did not notice any statement of the expected overall performance of the station in Btu per kwhr. Such a statement would be of wide interest as undoubtedly it would establish a new standard for steam stations.

In Table VI the station peak capacity is valued at $75 per kilowatt. Is one to infer that this is the estimated cost of the new Port Washington Station?

**I. E. Moultrop:** The design of the Port Washington Station described in the paper again points out the results that can be obtained by careful engineering study and intelligent economic analysis. While we may not agree with all of the conclusions advanced in the paper we know that at least the decisions are backed by the best engineering judgment. Many of us agree on the selection of the economical pressure for the new station, and it is hoped that the authors accomplish what they predict as a result of the steam temperature selected.

As we raise the operating steam temperature nearer and nearer the limit of the available materials of construction, the control of the steam temperature becomes increasingly important. It would be interesting to receive the operating results and to compare them with the design expectations as shown by curve 1. If the authors are able to obtain these flat steam temperature characteristics, they will have solved the major problem that has retarded the adoption of steam temperatures above 750 deg F, and will have gone a long way toward justifying the abnormally large furnaces used in their design.

We have recently made a careful study of the design of a new high pressure reheat station and our investigation showed a lower cost per unit of capacity for the cross-compound turbines with constant back pressure on the high pressure turbine as compared with the straight tandem-compound design. Furthermore, by the use of multiple-valve high and low pressure turbines and the proper heat balance arrangement, the same economy can be obtained above 60 per cent of full load and the difference in economy between the two designs is only 1.3 at 45 per cent of full load. The constant back pressure design has much to recommend it, and should not be discarded without careful study of all the advantages and disadvantages.

It is believed that The Milwaukee Electric Railway & Light Company is the only large utility still using the large "lazy flame" furnace with low heat release. Most new installations are designed for a heat release of twice that used in the Port Washington design and our studies indicate that the higher heat release designs should be cheaper to build. It will be interesting to hear later whether the lower furnace maintenance costs have justified this greater investment.

We must admit that the control of steam temperatures by means of desuperheaters is not all that could be desired, but it is workable and offers one solution of the problem.

The difficulties with, and high maintenance costs for economizers mentioned in the paper were true of the designs of 5 years ago, but the designs now offered by the manufacturers have eliminated most of the objectionable features. We feel that the economizer is an economical form of heat absorbing surface and has a place in the design of high pressure installations which cannot economically be replaced by the air heater or more boiler surface.

In view of the results being obtained in many stations with the unit system of pulverized coal firing, many of us cannot agree with the statements in regard to the comparative merits of this system in comparison with the bin system. We question especially the accuracy of the statement that in commercial operation the bin system will show 2.1 per cent better station economy than the unit system. We do not believe that this statement can be substantiated.

The design of the high pressure extraction heaters used is extremely interesting and shows a marked improvement over designs used in the past. This design seems to provide a sturdy piece of equipment that should be free from troubles and should not be unduly expensive to construct. The arrangement for undercooling the heater drips is an outstanding development.

Our studies confirm the conclusions of the author that outdoor iron-clad switches and structures are more expensive for 25,000 volts than indoor or combination indoor-outdoor designs. But our studies also have indicated that neither vertical nor horizontal isolation is justified economically when compared with the latest designs of non-isolated construction.

**R. C. Powell:** The studies for the design of the proposed plant for the San Joaquin Light and Power Corporation at Herndon, confirm, in general, the conclusions arrived at by Mr. G. G. Post, *viz.*, that a single boiler and turbine installation operating at 1,250 lb pressure and 850 deg F maximum temperatures for primary superheat and reheat is the best economically, all things considered, and is as reliable as lower pressures and temperatures. Due to favorable climatic conditions, both the boiler and turbine together with some of the heaters at Herndon were to be installed outdoors. The capacity for Herndon (75,000 kw maximum) approximated that of Port Washington.

Mr. Post's statement regarding inconvenience in operation and maintenance for the vertical compound unit is not confirmed by the experience at Station *A* after 2½ years operation with the type where the high pressure units are mounted on the low pressure generator. So far as can be determined to date, such units have neither operating nor maintenance disadvantages.

Mr. Post's statement as to an investment saving of $250,000 with 1 boiler over 2, checks very closely with an estimated saving at Herndon of $225,000.

Mr. Post's conclusions as to the relative costs of bent and straight tube boilers are confirmed by our studies, but experience at Station *A* with straight tube boilers does not confirm his conclusions that straight tube boilers are deficient in water storage and circulation, or do not furnish dry steam even when forced severely, also, that there is any difficulty as regards water wall connections or in the removal of suspended solids. At Station *A* the load on a turbine unit has been increased from 10,000 kw to 50,000 kw in approximately 35 seconds, with very little disturbance as regards pressure, temperature, or change in drum water level.

Undoubtedly, the use of coal would have considerable influence upon the selection of boiler equipment, but, at least with oil and gas fuel, the higher investment for a bent tube low heat release furnace is not justified. Nevertheless, the cost difference is not great and Mr. Post is sound in sticking to something that his own experience has proved so successful.

The writer fully agrees as to the advantages of high pressure heaters, although for somewhat different reasons than given. The experience at Station *A* with 1,600-lb pumps taking water at approximately the temperature given by Mr. Post, *viz.*, 430 deg F has been very excellent with no difficulty due to varying temperatures. There is, as mentioned, somewhat better economy by pumping at lower temperature, but the real advantage is in the simplicity of one pump as against two in series.

**Philip Sporn:** The conclusions as regards the mercury steam cycle, or even the less tried Benson cycle, most certainly are decisions that are justified fully in the light of the present available knowledge as to the success, plus or minus, of each of these two methods of generation. It is, however, open to question whether the conclusion to adopt the 1,200-lb, 825-deg reheat cycle was reached after exhausting all other possibilities. For example: although a comparison was made with the 600-lb reheat cycle, no figures are presented for the 600-lb, 825 deg non-reheat cycle. If any figures were developed in this connection, they would be most interesting.

In connection with the various phases of the heat cycle and the effect of fixed charges on them, Mr. Post uses a figure for fixed charges of 13 per cent. While this perhaps is adequate, it might be pointed out that with money taken at 7 per cent and taxes and insurance at 1 per cent, a total of 5 per cent is allowed for depreciation and/or obsolescence. Under certain conditions 5 per cent might not be sufficient. It is interesting, too, that the savings in fuel figured on the basis of a unit fuel cost of $3.80 per ton, would show up entirely differently if the fixed charges involved in the mining of fuel were taken into consideration. This, of course, was not necessary in connection with the Port Washington Station, but obviously it has to be taken into consideration in a not uncommon case where a plant and coal mine are operated as a unit. Again, from the broad national economic standpoint, it has a very definite significance.

The conclusions and the report of the results of the battle of storage *vs.* unit system of fuel firing are extremely interesting, but it is not quite certain that the battle has been fought entirely on fair grounds. It will be noted, for example, by referring to Table VI, that the burden of excess investments of the storage system in the amount of $59,112 is compensated by capitalizing the peak capacity resulting from the smaller electrical demand, at the rate of $75 per kilowatt. The writer wonders whether a consideration of the entire system as a unit, rather than only this particular station would not show that the difference in capacity required by the 2 fuel firing systems could not be met several times over by excess capacity in the form of overload capacity on running turbines, or in the form of standby capacity in idle turbines; capacity that would go unused as a result of the saving in capacity at this particular plant. If that is the case, it is obvious that the credit of $44,400 is not quite a sound credit.

The electrical phases of the plant with the 3-system of busses are extremely interesting, but one wonders whether all the switching end of the bus work involving a single unit really was considered indispensable before the final decision was made toward its installation. It would be interesting to find out whether a scheme was considered which utilized 3-winding transformers for the main power group having a 26.4-kv winding on the low side, with a 22-kv auto-tap on this winding, and 132-kv winding on the high side. If this did not give proper phase relations, a straight 3-winding transformer could be used. With a 3-winding transformer it would of course be possible to make the 22-kv side delta and the 26.4 and 132-kv windings *Y*, with the idea of furnishing the present as well as future local power requirements at 26.4 kv. This would eliminate entirely the 22-kv switching and have the further advantage of not subjecting the generators to any hazards that may result from feeding directly into overhead transmission lines from the generator terminals. Again, Mr. Post shows reactors behind all the 22-kv breakers, a further item of expense. It is obvious that the elimination of the 22-kv bus would have eliminated the necessity for these. As far as the effect on the short circuit capacity of the other voltages is concerned, they might have been handled by higher reactance transformers properly distributed among the 3 windings. In transformers of this size it is no great burden to obtain reactances up to 22 per cent. It would be interesting to find out whether such a scheme was considered and what were the reasons against its adoption.

Keeping in mind that a great deal of money is expended in switching, one wonders whether a scheme of tying together the auxiliary transformer to the main generator winding without a low tension switching was considered and why this was not utilized. For example, we have operated our Deepwater Plant that way for almost 3 years without any difficulty, and would duplicate such an arrangement today.

In connection with the splitting of the auxiliary load in 3 groups, namely, 2,300 volts alternating current, 480 volts alternating current and direct current, and the drawing of the line of demarcation between the two alternating current voltages at approximately 100 horse power, one is inclined to ask whether 550 volts was considered and if so, what the reasons were against its adoption. Most low tension switching equipment in the 480 voltage rating permits safe operation at 550 volts, and furthermore, with the newer oilless switching equipment, the economic limit of the lower voltage is closer to 250 horsepower than 100 horse power and permits a considerable saving by the elimination of the 2,300-volt switching equipment. Again, it would be interesting to find out why direct current service was adopted for the operation of turbine-room elevators, etc., and why it was further thought desirable and/or necessary to supplement that by battery service. It would appear that this was a refinement that could justify itself only in extreme conditions.

**G. G. Post:** In his discussion, Mr. E. J. Billings makes two suppositions in referring to Table IV, one that if the radiant superheaters and reheaters did not work out quite as anticipated the furnace maintenance credit of $5,700 per year over the high heat release slag tap furnace might become a debit, and the other, that for the same reason the credit of $3,900 per year for better furnace availability might also become a debit. Admittedly, there might be differences of opinion in various engineering phases of a plant of new design, such as this, but in the 2 examples cited by Mr. Billings, The Milwaukee Electric Railway and Light Company feels that it has made no rash assumptions for the bases of its calculations. The company has been a co-developer of radiant heat absorbing surfaces since 1923 and has at its disposal actual operating records and accurate data on such surfaces, to say nothing of the experiences gained through their use. Actual furnace maintenance costs (including water and steam walls) on the 4 high pressure boilers at Lakeside during the twelve-months' period ending July 1933, were $10,437 for 306,593 tons of coal burned, or 3.40c. per ton. The figure includes any and all replacements, none having been changed to capital or depreciation accounts.

As to availability, mention was made in the paper of the 93.7 per cent which these 4 boilers averaged during 1932. To date no comparable record for a boiler with a high heat release slag tap furnace has been found. In making the calculation for availability, it was assumed that the high heat release furnace would have an availability of only 2.5 points below that of the low heat release furnace:—87½ per cent against 90 per cent.

Mr. A. G. Christie inquired as to the basis for the selection of 60 per cent annual load factor for the various calculations in the paper. Sixty per cent annual load factor was selected because it is expected that Port Washington will be operated at this load factor without detrimental effects to the economy at Lakeside. High availability, proved possible by the Lakeside high pressure units, will assist in obtaining the 60 per cent load factor. Conditions at Lakeside, which will be the secondary plant of The Milwaukee Electric Railway and Light Company's system after Port Washington is in operation, are different than would ordinarily be expected because there the 1,200-lb cycle capacity is only 40 per cent of the total station capacity, the remaining 60 per cent being straight 300-lb equipment, some of which is over 10 years old.

In providing load for Port Washington, the load will in effect be transferred from the comparatively inefficient 300 lb section at Lakeside. This will tend to improve Lakeside's overall station economy, but also because of having to transfer a small amount from its 1,200-lb cycle during low load periods, Lakeside's overall station economy has been considered as remaining the same. This is reasonable especially in light of the fact that partial-load heat consumption on the Port Washington 1,200-lb cycle (compound operation) will be better than it is at Lakeside (constant back pressure). The transfer of load will not be as great as it may seem at present because by the time Port Washington goes into operation the load on the system as a whole will have increased.

In Mr. I. E. Moultrop's opinion, the 2.1 per cent better station economy for the storage system over the unit system cannot be substantiated. For Port Washington's design with its single boiler—single turbine, its large air heater without economizer, its radiant superheating and reheating surfaces, its higher steam and reheat temperatures (850 deg F maximum), and its mill drying with flue gas, and for conditions under which the station is expected to operate, each one of which enhances the difference, the 2.1 per cent is conservative. In order to show how this total was arrived at, the results of calculations for the component items follow:

***Reliability***

An outage or an interruption on any one of the 4 unit mills considered for the Port Washington installation would necessitate an immediate transfer of load to older equipment in another station where the heat consumption would be 2,500 Btu per kilowatt-hour power and coal would cost 66c. per ton more. Obviously, the economics of the case dictate operating Port Washington to its greatest possible extent. A statement by a company using both the unit and the storage system on an equal basis points out that in three months' operation it was necessary, due to difficulties with unit mills, to reduce the load on the station from 5,000 to 12,000 kw on 7 different occasions. Should only 0.5 per cent of Port Washington's total possible generation have to be transferred in a year, because of interruptions, to the poorer equipment whose heat consumption is 20 per cent poorer than Port Washington's, an 0.1 per cent loss in station economy would result.

| | | Storage | Unit |
|---|---|---|---|
| *Mill Drying* | | | |
| Reduced flue gas losses | | | |
| Due to 6 per cent of the flue gas discharged to stack at 150 deg F instead of at 350 deg F | per cent | 0.35 | 0 |
| Due to greater mean temperature difference and greater heat absorption in air heater | per cent | 0.40 | |
| Total gain | per cent | 0.75 | |
| Coal vent loss | per cent | 0.25 | |
| Net gain due to mill drying with flue gases | per cent | 0.50 | |
| *Temperature Variation* | | | |
| a. Coal feed variations without hand adjustments | per cent | 0 | 10 |
| b. Variation in $CO_2$ | per cent | 0 | 1.7 |
| c. Variation in radiant heat absorption | per cent | 0 | 20 |
| d. Change in reheat temperature, (deg F) | | 0 | 50 |
| e. Effect on station economy (1 per cent per 80 deg F on reheat alone) | per cent loss | | 0.6 |
| *Pressure Variation* | | | |
| a. Boiler pressure variation | lb/sq in. | 5 | 50 |
| b. Operating pressure, lb below popping point | lb/sq in. | 50 | 95 |
| c. Lesser operating pressure | lb/sq in. | | 45 |
| d. Effect on station economy | per cent loss | | 0.6 |
| *Air Heater Performance* | | | |
| a. Quantity of room air used for tempering air through mill | per cent | 0 | 10 |
| b. Resulting effect on flue gas exit temperature, deg F | | | 12 |
| c. Corresponding effect on boiler efficiency | per cent loss | | 0.3 |

*Summary*

| | |
|---|---|
| Greater reliability | 0.1 per cent |
| Mill drying gains | 0.5 per cent |
| Temperature variation gains | 0.6 per cent |
| Pressure variation gains | 0.6 per cent |
| Better air heater performance | 0.3 per cent |
| Total advantage of storage system | 2.1 per cent |

Mr. Philip Sporn takes exception to capitalizing the value of the greater kilowatt demand of the unit system motors at the time of the station peak, maintaining that the extra or overrating capacity of this station, or of others on the system, would be sufficient to absorb the small increase in demand created by these motors. While the argument may at first seem reasonable and it may be difficult to allocate certain station capacity to individual loads, it must be admitted that some station capacity is required, even for a load as small as that of a residential consumer. That this is recognized generally, is attested by the "demand charge" feature of electric service rates. In general, load cannot be put on a system without providing station capacity to carry it.

Another point mentioned is the omission from the comparisons of a table showing figures for the 600-lb, 850 deg F station operating without reheat. It was omitted because calculations showed that the 600-lb station with reheat effected a $16,100 larger net annual saving than did the 600-lb station without reheat, and therefore, the former was selected in making the comparison with the 1,200-lb cycle. Space did not permit printing this comparison nor many other interesting studies made for the Port Washington station.

Concerning the electrical features, reference to Fig. 5 will indicate that there is in reality but one bus in the station, this being the 22,000-volt bus. The 26.4-kv and 132-kv busses are for transfer purposes only. All switching is intended to be done at 22-kv and transformers are in effect portions of individual transmission lines. It was thought desirable to provide a 22,000-volt bus to effect economies in switching and to permit industries that might locate in the vicinity of the plant to connect directly to the bus bars without the need of transformation. This is important when it is remembered that such industrial load might amount to as much as 150,000 kilowatts. The use of a 22,000-volt bus dictated the use of reactors in all the lines except those supplying the transformers stepping up to 132 kv. Reactors are not necessary in the leads of the 132-kv transformers because the phase conductors are isolated. At the Lakeside plant, 10 overhead transmission lines operating at generator voltage are connected to the station bus through only a few hundred feet of underground cable and since no trouble has been experienced we do not believe there will be any hazard in similarly connecting overhead transmission lines at Port Washington.

In the auxiliary service 480 volts was used because this is the auxiliary voltage at Lakeside and also is a standard voltage on the company's system. The division between 2,300 volts and 480 volts was made at 100 hp because in the first unit of the station it would have cost $5,300 more to have made it at 250 hp.

The switching arrangement shown for the first unit is temporary in some respects but is such that it can easily be changed to conform to the expected ultimate arrangement. Three-winding transformers for the main power group were considered but were not adopted because no ultimate saving could be effected.

We have always considered it desirable to install oil circuit breakers between generator leads and auxiliary transformers so as to permit the disconnection of such transformers without interruption to service. The station is being built to operate at a high availability factor and in our opinion the relatively small additional expense for disconnecting the auxiliary transformer was justified.

Direct current service was adopted for certain equipment and backed up with a battery because this system will be used for reserve excitation and for driving the pulverized fuel feeders supplying coal to the furnaces. It is very desirable in case of system disturbances to be able to control the fires accurately in order to restore service more promptly.

# Progress in Three-Circuit Theory

BY A. BOYAJIAN[1]
Fellow, A.I.E.E.

## INTRODUCTION

AFTER some ten years of experience in the application of three-circuit theory to a variety of transformer problems, some limitations are encountered in the application of the elementary theory to certain types of problems. The purpose of this paper is to point out what these limitations are and how they may be circumvented.

## PRESENT THEORY

In a few words, present theory states that, so far as load characteristics are concerned, each circuit of a three-circuit transformer may be assigned an individual leakage impedance, and then no explicit thought need be given to any mutual inductive effects between circuits. Handling of three-circuit problems is remarkably simplified by this theory. It is generally assumed as applicable to all single-phase and polyphase circuits.

## LIMITATIONS OF THE THEORY

According to the above elementary theory, if two secondaries have identical impedances with respect to the primary, their individual leakage impedances will be equal and their simultaneous short-circuit currents will be equal and of the same power factor. Common sense (uncritical common sense) also would seem to demand such a conclusion, without any elaborate theoretical arguments. Recent experience has shown, however, that such is not necessarily the case in some polyphase transformers, and that particular attention to symmetry and the balancing of reactances may actually cause a large unbalance in load division. It is found further that such unbalance may change with change in the phase rotation of the excitation. Such anomalous behavior calls for a searching inquiry into the foundations of both theory and common sense. May it not be that we have generalized too far?

## EXAMPLE

Fig. 1 shows a transformer with a delta primary, and two oppositely zigzagged secondaries. For simplicity, assume all the zigs identical and those on each core leg perfectly interwound, and all the zags identical and those on each core leg perfectly interwound. It follows that $Z_{AB}$ must be identical with $Z_{AC}$. If $Z_{BC}$, which can be any value desired, also is given or calculated, the individual three-circuit impedances of the three branches, according to the well-known elementary theory, would be

$$Z_A = (Z_{AB} - Z_{BC} + Z_{CA})/2 = Z_{AB} - (Z_{BC}/2)$$
$$Z_B = (Z_{BC} - Z_{CA} + Z_{AB})/2 = Z_{BC}/2$$
$$Z_C = (Z_{CA} - Z_{AB} + Z_{BC})/2 = Z_{BC}/2$$

as shown in Fig. 2.

There is not the remotest hint in such an equivalent circuit that, if both $B$ and $C$ are simultaneously short-circuited, their currents may be displaced out of proper phase relationship with respect to each other and to the primary or that they may be grossly unequal numerically, or both, as shown by experience. Furthermore, there is nothing in such a diagram to indicate the possibility of reversal of load division with reversal in the phase rotation of the excitation, whereby the secondary which, with the former phase rotation, had the larger current may now have the smaller current.

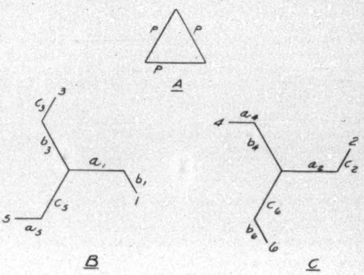


FIG. 1

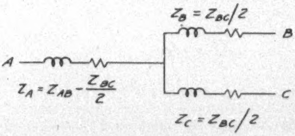


FIG. 2

What could be the explanation of such strange behavior?

## EXPLANATION OF PHENOMENA

A vector diagram may perhaps best serve to make this clear.

In order to simplify the matter, resistance will be ignored in this preliminary analysis, as it is included in the equations later on.

If 1, 3 and 5 in Fig. 1 are short-circuited to the neutral, the primary excited, and 2, 4 and 6 treated as voltmeter coil terminals, applying three circuit equations to the individual coils, instead of to the line terminals, we obtain vector diagrams like those shown in Figs. 3A and 3B.

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In Fig. 3A, $e_{a1}$ and $e_{b1}$ are the three-winding leakage impedance drops of coils $a_1$ and $b_1$, respectively. The dotted vectors $e_{a1}'$ and $e_{b1}'$ are the voltages delivered to those coils by the primary to overcome their impedance drops. Note that the total voltage consumed per phase (like the resultant of $e_{a1} + e_{b1}$), and the total voltage delivered per phase (like the resultant of $e_{a1}' + e_{b1}'$), are equal, as they ought to be, for the short-circuit condition; but, the voltage consumed by a coil, like $e_{a1}$, and the voltage delivered to that coil, like $e_{a1}'$, are not identical.

The vector diagrams of phases 3 and 5 are constructed in the same way as that of 1.

In Fig. 3B, the component voltages of phase 2 of the idle secondary are shown. Since coil $a_2$ is assumed interwound with $a_1$, it follows that $e_{a2}$ and $e_{a2}'$ will be the same as $e_{a1}$ and $e_{a1}'$. Similarly, since $c_2$ is interwound with $c_3$, their component voltages will be identical, and thus we get $e_{c2}$ and $e_{c2}'$. The resultant reactance voltage of phase 2 will be $e_2$; the resultant delivered voltage $e_2'$; and the resultant measurable terminal voltage $(e_2' - e_2)$. It may be seen that both the magnitude and the phase angle of $e_2$ will change with changed ratio of $e_{a2}$ and $e_{c2}$. It also may be seen that the measured voltage, $(e_2' - e_2)$ will change in magnitude and phase angle with changes in $e_2$, and may be either in phase, or in advance of, or lagging behind, the induced voltage of phase 2.

The interesting conclusion follows that, ignoring all losses, a zero power factor load in the secondary 1-3-5 may induce either a leading, or an in-phase, or a lagging voltage, in the secondary 2-4-6, depending on the ratio of the individual three-winding reactances of the zigs and the zags. That is, the mutual impedance due to a wattless current may have either a positive or a negative power component depending upon whether it is leading, or lagging behind, the voltage induced by the main flux.

If the reaction of a zero power factor load in the secondary 2-4-6, on the other secondary 1-3-5, is analyzed, similar to the foregoing, it will be found that if the load of the first secondary causes a lagging voltage in the second secondary, then the load of the second secondary will cause a leading voltage in the first secondary, as shown in Fig. 3C.

It follows from the foregoing that with currents of equal magnitude and power factor in the two sets of secondaries, their mutual action will tend to advance the voltages of one set of secondaries, and retard those of the other set, and will thus introduce a phase angle unbalance between the currents of the two sets of secondaries, in spite of the fact that the two sets are perfectly symmetrical by ordinary criteria. The phase angle unbalance may be better recognized if one considers the condition under which it would be absent. That condition is that, in Fig. 3B, $e_2$ coincides with $e_2'$; and, in Fig. 3C, $e_1$ coincides with $e_1'$, a condition which could be realized by properly proportioning the lengths of $e_{a2}$ and $e_{c2}$, or of $e_{a1}$ and $e_{b1}$, since, if one pair is proportioned properly, the other must follow by symmetry and interwinding for the present case. Under this condition, there will be no tendency for the two secondaries to drift from their normal angular relationship with respect to each other.

In a transformer to which Figs. 3B and 3C apply, if both secondaries are short-circuited, the currents in one will be advanced, those in the other retarded, with respect to their normal individual short-circuit currents. Since the normal is zero power factor, it follows from the advancing of one and the retarding of the other, that there will be a circulating power between the two secondaries.

Under the condition just considered, that is simultaneous short-circuit with negligible resistance, the unbalance in the currents will be one of phase angle only, the numerical values being the same. However, if the resistances of the windings also are taken into consideration, it will be seen that the circulating kilovoltampere will not be in quadrature with the normal share of each secondary in their simultaneous short-circuit kilovoltampere, but at an angle more than quadrature with respect to one secondary, and less than quadrature with respect to the other secondary, and thus there will result an unbalance in the magnitude of the currents of the two sets of secondaries, as well as in their phase relationship.

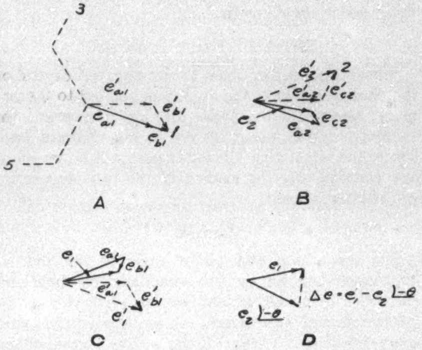

Fig. 3

If the two secondaries have identical load connected across them, their voltage regulations will be found dissimilar.

### Criterion of Balance or Unbalance

In Fig. 3D, $e_1$ is reproduced from Fig. 3C without any change; $e_2$ is reproduced from Fig. 3B retarded through the angle $\theta$ by which phase 2 normally leads phase 1. If in Fig. 3B $e_2$ had coincided with $e_2'$; and, in Fig. 3C,

$e_1$ had coincided with $e_1'$, then the two vectors in Fig. 3D would coincide with each other and their vector difference would be zero; but, otherwise, of course, not. *The dotted vector,* ($\Delta e = e_1 - e_2 \underline{/-\theta}$), *is therefore the unbalanced voltage which produces a circulating kilovoltampere between the two secondaries.*

This criterion applies whether or not the two secondaries are symmetrical. It also applies to the simpler cases, as in a transformer with one Y secondary and one delta secondary.

If the *magnitudes* of the rated circuit voltages are not the same, the vectors of Fig. 3D must of course be reduced to the same rated voltage basis. This condition is of course automatically satisfied if the impedance drops are expressed as percentages. If the *phase angles* of the rated circuit voltages are not the same, the vectors of Fig. 3D must be corrected for that also, as has been done already by retarding $e_2$ through the angle ($\theta$) by which its phase is normally in advance of the phase of $e_1$.

Equations for the determination of these vectors are developed in the appendix.

### Effect of Phase Rotation

Whether phase 2 or phase 1 is leading, will depend on the phase rotation of the excitation applied to the primary; because, if the phase rotation is reversed, the vectors $e_1$ and $e_2$ in Fig. 3D will be interchanged, and, hence, the circulating kilovoltampere will be reversed, and consequently the loading of the two secondaries will be interchanged.

### Testing

The magnitude and phase angle of the mutual impedances between the two secondaries for their load currents can be determined by test with the aid of voltmeters and wattmeters, one set of windings being short-circuited at a time. If the vector diagram of the normal voltages is known, the determination of the sign of the angles measured by the wattmeter is simplified. An a-c potentiometer would be very useful.

Simultaneous short-circuits on the two sets of secondaries would be the quickest means of determining the presence or absence of balance.

Another method of determining the mutual impedances is to short-circuit the primary, with excitation first on one set of secondaries, and then on the other.

### Condition for the Direct Applicability of Three-Circuit Theory

In generalizing from the foregoing illustration, it might appear that the anomalous behavior arises from the angular displacement or phase-shift between the two secondaries. However, that is not true. If one of the secondaries had been in Y, the other in delta, with 30 deg angular displacement between them, the strange phenomena mentioned above would not have taken place. Or, it might appear that the secondaries are six-phase and imply phase transformation, and that phase transformation is causing the anomaly. But that is not true either. Phase transformation from three to six can be obtained by double-Y or double-delta connection without giving rise to any such phenomena. Two-phase–three-phase transformation also may be accomplished with double secondaries without involving such anomalous behavior.

*These strange phenomena arise under conditions in which interconnection or cross connection of phases is involved, and said interconnection is different in one than in the other secondary.* For instance, considering secondary phases 1 and 2, it may be seen that their long coils are on the same core leg, but their short coils are on different core legs.

The truth of the foregoing point of view may be made clearer by reviewing the very reasoning on which three-circuit theory of polyphase circuits is based. Those familiar with the customary presentation of the subject will remember that three-circuit theory is first developed based on a single-phase transformer, and then the statement is made that what has been said holds true of each phase of a polyphase transformer, like a single-phase circuit, and is therefore directly applicable to a polyphase transformer. The generalization assumes, obviously, that each leg of the polyphase transformer is a pure single-phase circuit, and, consequently, if each leg is not a pure single-phase circuit, but consists of an interconnection of phases, the reasoning underlying the generalization does not necessarily apply to it any more. It would, however, apply to each coil because coils assigned individual impedances would constitute pure single-phase circuits among themselves. It must not be assumed, however, that all circuits with interconnected phases must necessarily be capable of behaving anomalously.

Since it is not possible to anticipate the infinite variety of possible transformer connections involving interconnection of phases, how can we state in a general way the condition under which the elementary three-circuit theory and network are directly applicable to them and adequate? Possibly in the following manner:

### Theorems

1. Single-phase three-circuit equivalent networks and equations are directly applicable to polyphase circuits, provided that there is the same angular displacement between the self- and mutual-load impedances, as between the normal induced voltages.

2. When there is no cross-connection between phases, the above condition is satisfied automatically; but when such cross-connection exists, the above condition may or may not be satisfied. In at least the simpler symmetrical cases, the impedances may be so designed as to satisfy the above condition.

3. When the condition in (1) is not satisfied, three-circuit theory still may be applied, but to the individual component coils only, to obtain the resultant voltages at the line terminals.

## Appendix

### GENERAL EQUATIONS

Referring to Fig. 1, with $I_1$, $I_3$ and $I_5$, and $I_2$, $I_4$ and $I_6$, as percentage currents in the corresponding lines; $k_{a1}$, etc., representing the voltage of $a_1$ as a fraction of the line-to-neutral voltage of phase 1, etc.; the various impedances expressed as percentages to a common kilovolt-ampere basis; the resultant per cent impedance drop in a representative phase in each secondary will be,

$$\begin{aligned} e_1 = \{ I_1 [ & Z_{p(a_1a_5)}\, k_{a1}^2 + Z_{a1(pa_5)}\, k_{a1}^2 \\ & + Z_{p(b_1b_3)}\, k_{b1}^2 + Z_{b1(pb_3)}\, k_{b1}^2] \\ & - I_5\, Z_{p(a_5a_1)}\, k_{a5}k_{a1} - I_3 Z_{p(b_3b_1)}\, k_{b3}k_{b1} \} \\ & + \{ I_2 Z_{p(a_2a_1)}\, k_{a2}k_{a1} - I_4 Z_{p(a_4a_1)}\, k_{a4}k_{a1} \\ & + I_6 Z_{p(b_6b_1)}\, k_{b6}k_{b1} - I_4 Z_{p(b_4b_1)}\, k_{b4}k_{b1} \} \end{aligned}$$

in which the quantities within the first pair of braces represent the drops in phase 1 due to the currents in the secondary *B*; and the quantities within the second pair of braces, the impedance drops in phase 1 occasioned by the currents in the secondary *C*. Similar to the foregoing,

$$\begin{aligned} e_2 = \{ I_2 [ & Z_{p(a_2a_4)}\, k_{a2}^2 + Z_{a2(pa_4)}\, k_{a2}^2 \\ & + Z_{p(c_2c_6)}\, k_{c2}^2 + Z_{c2(pc_6)}\, k_{c2}^2] \\ & - I_4 Z_{p(a_4a_2)}\, k_{a4}k_{a2} - I_6 Z_{p(c_6c_2)}\, k_{c6}k_{c2} \} \\ & + \{ I_1 Z_{p(a_1a_2)}\, k_{a1}k_{a2} - I_5 Z_{p(a_5a_2)}\, k_{a5}k_{a2} \\ & + I_3 Z_{p(c_3c_2)}\, k_{c3}k_{c2} - I_5 Z_{p(c_5c_2)}\, k_{c5}k_{c2} \} \end{aligned}$$

These general equations can be simplified a great deal in practical cases either by symmetry or duplication of coils, or both. For instance, assuming that the long and the short coils of *B* are the duplicates of the corresponding long and short coils of *C*, only two *k*'s need be used: $k_l$ for the long coils, and $k_s$ for the short coils. Furthermore, if all the long coils on each leg are interwound, and similarly all the short coils on each leg interwound, only three coil designations and corresponding individual three-circuit impedances need be used: $Z_p$ for the primary, $Z_l$ for the long coils, and $Z_s$ for the short coils. $Z_{p(a_1a_2)}$ becomes $Z_{pl}$, and $Z_{p(b_1b_6)}$ becomes $Z_{ps}$. With these substitutions, the foregoing equations reduce to,

$$\begin{aligned} e_1 = \{ I_1 [ & Z_p k_l^2 + Z_l k_l^2 + Z_p k_s^2 + Z_s k_s^2] \\ & - I_5 Z_p k_l k_s - I_3 Z_p k_l k_s \} + \{ I_2 Z_{pl} k_l^2 \\ & - I_4 Z_p k_l k_s + I_6 Z_{ps} k_s^2 - I_4 Z_p k_l k_s \} \end{aligned}$$

$$\begin{aligned} e_2 = \{ I_2 [ & Z_p k_l^2 + Z_l k_l^2 + Z_p k_s^2 + Z_s k_s^2] \\ & - I_4 Z_p k_l k_s - I_6 Z_p k_l k_s \} + \{ I_1 Z_{pl} k_l^2 \\ & - I_5 Z_p k_l k_s + I_3 Z_{ps} k_s^2 - I_5 Z_p k_l k_s \} \end{aligned}$$

Further simplification may be effected by combining and rearranging the terms as follows:

$$\begin{aligned} e_1 = \{ & I_1 (Z_{pl} k_l^2 + Z_{ps} k_s^2) - (I_3 + I_5)\, Z_p k_l k_s \} \\ & + \{ I_2 Z_{pl} k_l^2 - 2 I_4 Z_p k_l k_s + I_6 Z_{ps} k_s^2 \} \end{aligned}$$

$$\begin{aligned} e_2 = \{ & I_2 (Z_{pl} k_l^2 + Z_{ps} k_s^2) - (I_4 + I_6)\, Z_p k_l k_s \} \\ & + \{ I_1 Z_{pl} k_l^2 - 2 I_5 Z_p k_l k_s + I_3 Z_{ps} k_s^2 \} \end{aligned}$$

In general $I_3$ and $I_5$ may be assumed as symmetrical with $I_1$ and expressed in terms of $I_1$; similarly, $I_4$ and $I_6$ may be assumed as symmetrical with $I_2$ and expressed in terms of $I_2$, so that only two independent currents, $I_1$ and $I_2$, need appear in the equations. Then, if $e_1$ and $e_2$ are given (as, for instance, for simultaneous short circuits $e_1$ and $e_2$ are the respective no-load phase voltages) then $I_1$ and $I_2$ may be solved for, vectorially. Or, if $I_1$ and $I_2$ are given, then $e_1$ and $e_2$ (the vector voltage drops in the respective phases), and hence the regulation of the two sets of secondaries, may be calculated.

The voltage unbalance resulting from normal symmetrical balanced currents in the two sets of secondaries will be

$$\begin{aligned} e_1 - e_2 \underline{/ - \theta} = & (I_2 - I_1 \underline{/ - \theta})\, Z_{pl} k_l^2 \\ & - 2\,(I_4 - I_5 \underline{/ - \theta})\, Z_p k_l k_s + (I_6 - I_3 \underline{/ - \theta})\, Z_{ps} k_s^2 \end{aligned}$$

For perfect balance between the two secondaries, the foregoing equation must be equal to zero. Accordingly, if $k_l$, $k_s$ and $\theta$ are given, the proper ratio of $Z_p$, $Z_l$, and $Z_s$ may be determined to make the equation zero. Since $\theta$ is dependent on the relative length of *l* and *s* coils, it will be found that $Z_p$ may be cancelled out in the foregoing when $Z_{pl}$ is replaced by $(Z_p + Z_l)$, and $Z_{ps}$ replaced by $(Z_p + Z_s)$.

# The Polarity Factor in the Kindling of Electric Impulse Sparkover Based Upon Lichtenberg Figures

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***Synopsis.***—*The paper presents the results of a photographic study of successive steps in the kindling process of impulse sparkover in unsymmetrical dielectric fields. The photographs confirm the theory, established by the bending of the electric figure streamers when formed under stress of the magnetic field, that electrons primarily are the active elements in the kindling mechanism. The figures also indicate that in a field of ionizing potential gradient the bridging of the spark-gap (10.5 cm) is due largely to extension of the streamers or channels from the positive electrode; and that space charges affect the impulse-sparkover process.*

## INTRODUCTION

THE effects due to polarity in high voltage electric phenomena have not received attention commensurate with their importance. By far the greater number of investigations by engineers on the nature of high voltage discharges have been made on symmetrical or homogeneous dielectric fields; using electrodes essentially of the same size and shape: two like needle points, two spheres of the same size, or two parallel wires of like diameter. Comparatively little work has been done on unsymmetrical or non-homogeneous fields, using electrodes differing in size and shape:[1,2,3,4] as needle point to sphere, needle point to plane, sphere to plane. Moreover, no equations or quantitative relations have been developed for correlating the like electrode experiments to conditions of unsymmetrical dielectric fields, as existing with electrodes differing in size and shape.

Extended investigations by engineers on high voltage phenomena relate, in the main, to alternating currents, largely because the most urgent need for more information on electric discharges, as corona and sparkover, developed in connection with the rapid expansion of alternating current, electric power systems. Interest has been primarily centered on high tension problems relating to the design and operation of alternating current transmission systems, particularly with reference to corona and to transient electric phenomena caused by switching and by lightning. But even for alternating currents very little is known about the mechanism of sparkover, corona and other forms of electric discharges. The experimentally determined quantitative relations for producing corona, sparkover or other forms of electric discharges still are expressed, at best, by empirical equations that apply only under limited, specified conditions. Reliable experimental data that may be used as a basis, even for empirical solutions of direct or unidirectional, high-voltage, electric-discharge problems, are meager and for many cases entirely lacking.

In lightning investigations the polarity factor has of necessity received much attention, but the lack of adequate basic information on the nature of, and the difference in, the mechanisms of the air breakdown process at the positive and the negative electrodes has made it impossible to interpret the accumulated data satisfactorily.

The experiments described in this paper were made in order to obtain *photographic evidence relating to polarity effects for electric impulse-sparkover* in unsymmetrical or non-homogeneous dielectric fields. In order to keep the experimental conditions as simple as possible, the investigation was limited to the initial or *kindling stage of impulse-sparkover and the energy content of the impressed potential impulse was kept very small to minimize, as much as possible, the thermionic effects.* This implies that the duration of the electric impulse at peak voltage must be made very short—a microsecond or less—and that, in order to stop the sparkover process at any desired point, the quantity of energy discharged must be correspondingly small. The electric impulses either were strictly non-oscillatory or had very slight polarity reversals. The potential impulses, as determined by cathode-ray oscillograms, had wave fronts of approximately 2½ microseconds and of very short peak duration. However, the time required to form the electric figures is only a fraction of a microsecond; the velocity of formation, according to Pedersen,[6] being approximately $4 \cdot 10^7$ cm per sec.

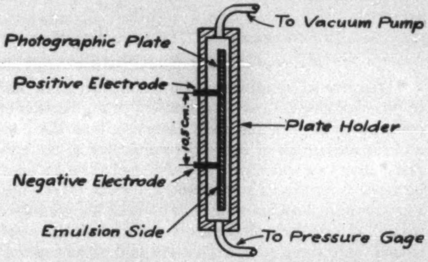

FIG. 1—CROSS-SECTION OF PLATE HOLDER SHOWING POSITIONS OF ELECTRODES AND PHOTOGRAPHIC PLATE

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1. For references see bibliography.

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To obtain strictly non-oscillatory impulses of steep wave front, of high voltage and short time-duration, is a difficult laboratory problem. This is evidenced by attempts to explain reversal of polarity in the figures as being due to a backwash or reaction[4] from the space-charges produced during the initial stage of the figure-forming impulse. The complete absence of any reversal at either electrode, as shown in Figs. 5, 6, 7, 8 and 9, proves that this assumption is not well founded.

The usual method of inserting resistance in the discharge circuit to prevent oscillations cannot be used to advantage, as the resistance affects the steepness of the wave front and the resulting forms of the electric figures. Non-oscillatory discharges having the desired steep wave fronts were obtained: by thoroughly grounding one of the terminals connected to the photographic plate; by having as little inductance as possible in the discharge system; and by using a *trickling charge* process in raising the sphere-gap to the required sparkover potential. The automatic series discharge from parallel-charged circuits, generally used in high voltage impulse generators, could not be used, as the resulting figures indicate oscillatory discharges.

In order to record photographically the effects produced by the polarity factor in electric impulse sparkover, two types of electrode arrangements were used.

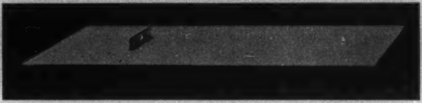

FIG. 2—PHOTOGRAPHIC PLATE WITH BARRIER

1. A barrier, after Marx,[2] placed near one of the two like electrodes forming an obstruction in the direct sparkover path.
2. Electrodes differing in size and shape.

BARRIER EXPERIMENTS

A cross-section of the plate holder, with photographic plate in position is shown in Fig. 1. The ends of the 2 electrodes, cylindrical rods 0.2 cm in diam, spaced 10.5 cm apart, and attached to the cover of the holder are in contact with the emulsion surface of the photographic plate (Eastman Speedway).

A glass barrier, 4 cm long, 0.5 cm high and 0.2 cm thick was placed on edge near one electrode so as to form an obstruction in the direct sparkover path, as shown in Fig. 2. The barrier was firmly attached to the photographic plate by means of bakelite cement.

The ohmic resistance of the emulsion film on the photographic plate (Eastman Speedway) at room temperature, measured by low voltage galvanometer or wheatstone bridge methods; was found to be very high, approximately one-tenth that of the glass itself. For continued application of even moderate voltages the resistance of the emulsion film decreases rapidly.

The sharpness of outline of the electric (Lichtenberg) figures, as well as the marked tendency of the sparkover path, produced by impulse potentials, to follow the emulsion film surface in preference to more direct and considerably shorter routes through the surrounding air, may indicate that the air resistance at the plate surface is less, or that ionization occurs more readily on or very near to the film surface, than in the open air space.

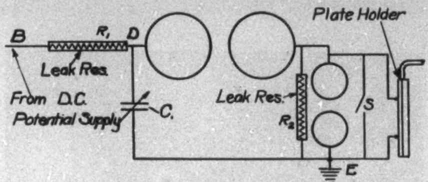

FIG. 3—CIRCUIT DIAGRAM

Diam of spheres: 25.4 cm and 10.0 cm, respectively; $R_1$: 2,000 to 100,000 megohms; $R_2$: 254 megohms; $C_1$: variable, from 100 to 1,400 microfarads. Section *D-E*: non-oscillatory discharge circuit

The presence of the photographic plate in the space near the electrodes necessarily affects the distribution of the dielectric flux. The higher permittivity of the photographic plate (glass and emulsion film) combined with the modified ionizing properties of the air layer in contact with, or very near to, the film surface probably affect the potential gradient of the impulse wave and the resulting paths or figures. The circuit diagram for the electric figures illustrating this paper is shown in Fig. 3.

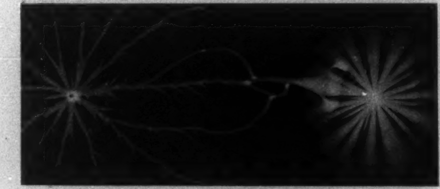

FIG. 4—POINT ELECTRODES, SPACED 10.5 CM

Air pressure: 20.0 cm Hg; spark gap: 2.00 cm

The d-c power supply consisted of 21 condensers charged in 3 parallel groups, but connected in series during the discharge operation. The energy charge that produced the electric figures was transmitted from the supply at *B*, to the sphere spark gap, through the high resistance $R_1$ (from 2,000 to 100,000 megohms); increasing the potential at the point *D* until the spark gap discharged to ground. With the supply voltage sufficiently high, a rapid succession of sparkovers would occur. The switch, $S$, was kept closed, short-circuiting the plate holder, except during the discharge of a single sparkover, which produced the desired non-oscillatory, electric figures on the photographic plate. For most of the photographs illustrating this paper, only the energy stored in the sphere gap itself (approximately $2.10^{-6}$ $\mu$f) entered into the discharge.

The potential of the impulse wave is expressed in terms of the main circuit spark-gap spacing, which could be definitely measured, instead of in computed kilovolt, because the space-charges formed at the plate holder electrodes and in the spark gap introduced variations, the magnitude of which could not definitely be determined.

FIG. 5—AIR PRESSURE: 30 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm) 0.8 cm from *negative* electrode. Circuit spark gap: 2.5 cm

The non-oscillatory discharge circuit, Fig. 3, produced impulse-sparkovers of steep wave fronts and of small energy content. However, although the energy content was small, the electric power, during the discharge, was large as the time in which the figures were formed was very short, in the order of $10^{-7}$ seconds. For the discharges at atmospheric pressure more energy was required, which was provided by means of the variable condenser $C_1$. Several sets or series of exposures, for varying impulse potentials, were made at air pressures of 18, 30, 50 and 76 cm hg, respectively. Although the change in air pressure caused well known modifications in the size and appearance of the electric figures, the kindling mechanism of the sparkover process appears to be essentially the same throughout the range covered by the experiments.

FIG. 6—AIR PRESSURE 18 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *positive* electrode. Circuit spark gap: 1.2 cm

To distinguish more readily the effects resulting from a barrier placed in the direct sparkover path a pair of electric figures produced by arrested sparkover between point-electrodes (symmetrical dielectric fields, and without barrier), is shown in Fig. 4.

With a glass barrier firmly attached to the emulsion surface, as shown in Fig. 2, and by placing the plates in the holder, so as to have the barrier at either the positive electrode, as in Fig. 6, or at the negative electrode, as in Fig. 7, several series of exposures were made; with impressed impulse-potentials, duration of peak-potentials and air pressures the variable factors. The photographs obtained give evidence that not only the impulse potential and air pressure affected the form of the electric figures but likewise the duration of the peak potential, or the quantity of energy released by the discharge.

At the higher air pressures and for producing complete sparkover, the energy content of the discharge was varied by means of the condenser $C_1$, Fig. 3. The successive steps, or stages, in the electric discharge figures were obtained by adjusting the discharge circuit so that the energy content of the impulse recorded had just spent itself at the desired point in the sparkover process.

FIG. 7—AIR PRESSURE: 35 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *negative* electrode. Circuit spark gap: 4.0 cm

The effects produced on both the negative and positive Lichtenberg figures by a barrier placed in the direct path between the electrodes, as illustrated in Figs. 5 to 9 inclusive, are in full accord with the basic principle that electrons and not positive ions form the active elements in the kindling mechanism of electric impulse-sparkover. Specifically it is assumed:

1. At the negative electrode: that at the start, or during the initial step, (formation of the negative electric figure) electrons are projected away from the negative electrode.[10]

2. At the positive electrode: that at the start, or during the initial step, (formation of the positive electric figure) electrons move towards and fall into the positive electrode, as suggested by Nipher[7] (1910), by Yoshida[8] (1917), and experimentally proved[6] in 1930 by the bending of the streamers of the electric figures, when formed under stress of the magnetic field.

3. That the positive streamers develop away from the positive electrode[11] (the electrons moving towards the positive electrode), as long as the potential gradient at the tip of the streamer is sufficiently high to produce ionization.

4. That the positive streamers during the formative stage (ionization by collision) are paths or channels of comparatively low resistance.

The effects of the barrier, on both the negative and positive figures, are in full accord with the above assumptions.

*First.* If the barrier is near the negative electrode, as in Figs. 5 and 7. In no case did electrons pass under or through the barrier. The parts of the negative figure appearing on the left side of the barrier in Figs. 5 and 7 are not an extension of the electron stream originating at the negative electrode. It is evident that, if the potential gradient of the impulse be of intensity sufficient to produce ionization on the left side of the barrier, the negative streamers would be formed outside the barrier. Hence, the negative streamer segments, although appearing on both sides of the barrier, are formed independently but by the same process, namely: ionization and projection of electrons radially away from the negative electrode.

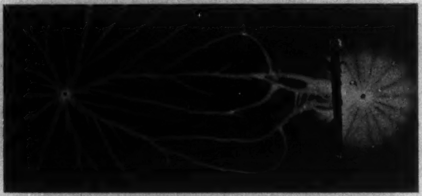

FIG. 8—AIR PRESSURE: 18 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.7 cm from *negative* electrode. Circuit spark gap: 1.4 cm

*Second.* If the barrier is near the positive electrode, as in Figs. 6 and 9, the effects are strikingly different. It is evident that the streamers passing around the corners of the barrier can not be formed by ions projected from the positive electrode. On the assumption that the positive streamers are formed by electrons moving towards, or falling into, the positive electrode it becomes clear why the streamers pass around the ends of the barrier. Only at the tips of the positive streamers (paths or channels of low resistance), would the potential gradient be of sufficient intensity to produce ionization and thereby cause extension of the positive streamer channels towards the negative electrode.

The initial formation of the electric figures may be considered as *the first step or stage in the impulse-sparkover kindling process.* Under critical potential gradient conditions, an increase in the energy content of the impressed impulse, or a slight increase in the impressed impulse peak-potential, or a decrease in the air pressure, produces marked extension of the positive streamers towards the negative electrode, with comparatively little increase in the size of the negative figure, as illustrated by Figs. 7, 8 and 9. That the extension of the positive streamers or channels comes after the formation of the negative figure is evident from the photographs, as in Figs. 4 and 9 which indicate that the filaments or terminals of the positive streamers were superimposed on the negative figure. The presence of the barrier in Figs. 8 and 9, produces distortions in the figures but it still appears that, whether the barrier is near the positive or the negative electrode, the spanning of the intervening gap is accomplished largely *by the extension of the positive-figure channels with little, if any, increase in length of the negative streamers.*

FIG. 9—AIR PRESSURE: 17.1 CM HG, ELECTRODES SPACED 10.5 CM

Barrier (4 cm x 0.5 cm), 0.6 cm from *positive* electrode. Circuit spark gap: 2.4 cm

It should be noted also, that in arrested sparkover, as in Figs. 4 and 9, the positive streamers do not reach the negative electrode but end or spread, as more or less distinct branches or filaments, in the outer radial half of the negative Lichtenberg figure. The spreading of the filaments is due probably to a negative space charge at the periphery of the negative figure in combination with a positive space charge surrounding the negative electrode. If the peak potential of the impulse is sufficient in magnitude and duration to overcome the posi-

FIG. 10—POINTED ELECTRODE NEGATIVE. ELECTRODE SPACING: 8.2 CM

Air pressure: 50 cm Hg. Spark gap: 1.6 cm tive space charge near the negative electrode, the positive streamers extend to the negative electrode and form a continuous conducting path of comparatively low resistance, which may develop into complete breakdown.

### ELECTRODES DIFFERING IN SIZE AND SHAPE

A large number of discharge photographs were taken, with impulse potential, energy content and air pressure, as variables, for several sets of electrodes differing in size and shape. Under the conditions required for producing a photographic record the electrode forms that can be used are limited by the presence of the glass plate or film to point-point, point-line (straight or curved) and modified point-plane forms.

In Figs. 10 and 11, the spark-gap consisting of a small pointed electrode and a straight edge with rounded corners determines the flux distribution of the unsymmetrical dielectric field. These figures were selected as typical from a series taken at constant air pressure (50 cm Hg) and spacing (8.2 cm) with impulse potential variable.

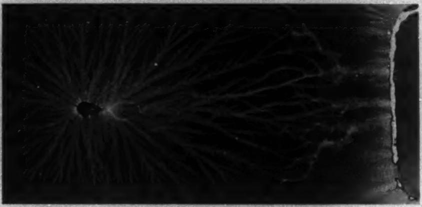

FIG. 11—POINTED ELECTRODE POSITIVE. ELECTRODE SPACING: 8.2 CM

Air pressure: 50 cm Hg. Spark gap: 1.4 cm

The assumptions made for the preceding barrier experiments likewise apply to Figs. 10 to 14. The *first step* in impulse sparkover is the formation of Lichtenberg figures, the shapes of the electrodes greatly affecting the respective sizes of the positive and negative figure. In the *second step*, as shown in Figs. 10 and 12, the positive streamers increase in length and bridge the space between the initial electric figures formed around the two electrodes. It should be noted (Fig. 10) that the positive streamer, on reaching the space covered by the previously formed negative figure, divides into several filaments spreading the outer radial half of the negative figure, but not extending directly to the negative electrode.

With the pointed electrode positive, as in Fig. 11, the positive streamers extend over a much larger part of the electrode spacing than with the pointed electrode negative, as in Fig. 10. As noted under the barrier experiments the negative figure streamers are formed mainly during the initial stage or step in the process; the part of the sparkover gap being bridged by extension of the positive streamers. A point-plane spark gap in contact with a photographic plate is shown in Figs. 12 and 13. One electrode consisted of a brass plate or bar having slightly rounded edges, placed on top of the photographic plate with the plane surface at right angles to the emulsion film. The other electrode was a cylinder of 1 mm diam having one end in contact with the emulsion surface. The combination may be considered as equivalent to a gap of physical form in between that of point plane and point line. The presence of the photographic plate also modifies the distribution of the dielectric flux in the intervening space, as compared to an ordinary air-filled, point-plane spark gap.

FIG. 12—POINT ELECTRODE NEGATIVE. ELECTRODE SPACING: 9.5 CM

Air pressure: 40 cm Hg. Spark gap: 3.95 cm

In Fig. 12, with the plane surface positive, a number of streamers are formed and a single positive streamer extends to the negative figure but does not reach the negative electrode. With the point positive, as in Fig. 13, three positive streamers completely span the gap, although the impressed impulse potential was slightly lower than in Fig. 12. In Fig. 13, with the plane surface the negative electrode, the negative figures are very small—barely visible, while with reversed polarity as in Fig. 12 the positive Lichtenberg figures are large and sharply defined.

FIG. 13—POINT ELECTRODE POSITIVE. ELECTRODE SPACING: 9.5 CM

Air pressure: 40 cm Hg. Spark gap: 3.90 cm

This markedly different extension characteristic of the positive, as compared to the negative streamers, may be, and probably is, the basic cause for the wide difference in sparkover potentials, for point-plane[2,3] spark gaps, under reversed polarity conditions. It is evident that complete sparkover would occur at lower sustained peak potentials for point positive and plane negative, as illustrated by Fig. 13 than for the point negative and plane positive combination, as in Fig. 12.

### SPACE CHARGES

In a notable investigation[9] (Kerr cell electro-optical shutter) on static breakdown of short spark gaps (1.25 to 10 mm) Dunnington finds that space-charges in the gap are important factors in the sparkover process. Space-charge distribution is shown for two types of breakdown under specified conditions. He also notes *l.c.*, p. 1545) that the multiplicity of filament frequently observed in the later stages of the breakdown occurs in the spaces occupied by the negative charges.

It appears probable that similar space charges will be formed under impulse sparkover conditions; that immediately after the impulse discharge producing Lichtenberg figures, as in Fig. 4, a positive charge surrounds the negative electrode, a negative charge covers the outer radial part of the negative figure with a positive charge in the region of the positive streamers. Several observed effects, as the positive figure streamers of electric figures formed by two successive impulses do not overlap; or the extension of the positive streamers with the spreading of the streamer tips over the outer radial section of the negative figures, as illustrated in Figs. 4, 9, 10 and 12, may be explained on the above assumptions.

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## Discussion

**F. O. McMillan:** Doctor Magnusson's contention that the effects due to polarity in high-voltage phenomena have not received the attention commensurate with their importance certainly is well taken. He calls attention to some of the electrodes that produce symmetrical dielectric fields and have been extensively studied by engineers, and further enumerates some of the electrodes that produce unsymmetrical fields and need to be investigated in much more detail. The electrodes named in the list of those producing unsymmetrical dielectric fields are all very important, but one that produces a distorted field and which is very important, because it is so generally used for high-voltage measurements, has not been specifically mentioned. Attention should be directed to the use of 2 spheres of the same size with 1 sphere grounded for measuring alternating and impulse voltages, The importance of considering this electrode combination is shown by the fact that practically all high-voltage laboratories employ grounded circuits for both alternating and impulse voltage tests, and use grounded sphere-gaps extensively for making high-voltage measurements.

It is recognized generally that a grounded sphere gap does not have a symmetrical dielectric field even when used in accordance with the Standards of the A.I.E.E. for the measurement of test voltages in dielectric tests. The distortion of the field is shown clearly by the experimental fact that the sparkover voltages for all but the relatively close sparking distances are lower with 1 sphere grounded than with both spheres insulated, and the further fact that this difference between the grounded and ungrounded sparkover voltages becomes greater as the ground plane is brought nearer to the spark-point of the grounded sphere. Notwithstanding these well known data showing the grounded sphere gap dielectric field to be seriously distorted, unidirectional impulse voltage measurements, made with grounded sphere gaps and evaluated by the use of the low frequency alternating voltage calibration curves for such gaps, have been almost universally used and accepted.

In September 1930 a paper[1] was presented before the Pacific Coast Convention of the A.I.E.E. in which data were given showing the polarity characteristics of grounded sphere gaps for both 60 cycle and impulse voltages. See Tables IV to VIII and Figs. 9 to 14 in the above paper. These data show that 60-cycle symmetrical voltages spark over grounded sphere gaps on both polarities only at relatively very close sparking distances, at intermediate spacings sparkover always occurs when the ungrounded sphere is negative and at wide separation, beyond the sparking distances recommended by the Standards of the A.I.E.E., there is a rather abrupt transition where the negative sparkover voltage becomes greater than the positive and for sparking distances greater than this critical spacing grounded sphere gaps always spark over when the ungrounded sphere is positive. This phenomenon, sparking over on 60-cycle symmetrical voltage only when the spheres have definite polarity relationships, shows conclusively that the positive and negative sparkover voltages must be quite different for the sphere separations that select one sparkover polarity continuously, otherwise grounded sphere gaps would spark over on either polarity indiscriminately at all sparking distances. The grounded sphere gap sparkover data obtained with unidirectional impulse voltages of both polarities show excellent correlation with the 60-cycle data. At relatively short sparking distances no appreciable difference was found in the positive and negative impulse sparkover, at intermediate spacings the sparkover voltage was lower when the ungrounded sphere was negative than when it was positive and at long sparking distances (considerably longer than one sphere diameter) the negative sparkover rapidly approached the positive value, became equal to it, and then increased to a value considerably larger. The maximum differences observed between the positive and negative sparkover voltages are very much larger than the permissible errors of measurement in high voltage testing. The error is especially large near the upper limit of the range of sparking distances recommended by the Standards of the A.I.E.E. Therefore, calibration curves for each polarity are necessary when grounded sphere gaps are used to measure both positive and negative unidirectional impulse voltages. The work that has been done indicates that the present standard alternating voltage calibration curves are quite accurate for impulse voltages when the ungrounded sphere is negative, but the positive values of voltage indicated by the use of these curves are much too low. The latter is especially true when voltages are measured near the maximum recommended sparking distance for a particular size of spheres.

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[1] *The Influence of Polarity on High-Voltage Discharges*, by F. O. McMillan, A.I.E.E. TRANS., Vol. 50, March 1931, p. 23.

The polarity phenomenon exhibited in the sparkover characteristics of grounded sphere gaps, when used to measure 60-cycle symmetrical alternating voltages, apparently is limited to scientific interest only at the present time. A low frequency alternating voltage will only very rarely, if ever, be increased at a sufficiently rapid rate to obtain a very large difference in crest-voltage between successive waves of opposite polarity; therefore, a grounded sphere gap measures such voltages satisfactorily even though there is a marked difference in the positive and negative sparkover voltage.

In the discussion of the difficulty of obtaining non-oscillatory impulses of steep wave front, Doctor Magnusson refers to a theory of the formation of Lichtenberg figures given in the paper previously discussed.[1] The part of this theory explaining the formation of the small superimposed figures of reversed polarity, by the action of the voltage gradient produced by the residual ion space charge that remains when the electrode potential is removed quickly, after an unidirectional impulse figure is formed, is not well founded. This opinion is reached because it is concluded that Figs. 5, 6, 7, 8, and 9, formed by point electrodes with barriers in various positions, do not show any reversed figures superimposed on the original figures at either electrode. It should be pointed out that the theory was developed to explain the behavior with the usual electrode arrangement used in klydonographs and surge-voltage recorders, that is, a point to a relatively large insulated plane or cylinder with the point resting on the photographic emulsion and the plane directly back of it on the opposite side of the film or plate. The Lichtenberg figures cited were formed between two point electrodes with relatively wide separation and both located on the emulsion side of the photographic plate. This arrangement will alter greatly the flux distribution and electrode gradient, and make it necessary to apply a higher voltage to produce a given figure size. This in turn probably materially reduces the size of the superimposed figure, of reversed polarity, that can be formed by the residual space charge. Notwithstanding this fact, it is difficult to concede that these Lichtenberg figures do not have small reversed figures especially at the positive electrode. The half-tone reproductions, no doubt, have lost much of the detail shown in the original photographic negatives; however, around the point of contact of the positive electrode, shown by a black spot in the half-tone reproduction, it will be observed that there is a small bright white ring that shows much greater photographic exposure than any other portion of the positive figure. Investigations carried on in 1930 led to the conclusion that this intense exposure area on the positive figure is actually a small superimposed negative figure. It is difficult to account for this area in any other way, because it can be increased in size without discontinuity by increasing the rate at which the potential is reduced on the electrode after the initial figure is fully formed, and it can still further be increased in size by actually reversing the electrode potential. As the latter is done the superimposed negative figure is much larger than the applied reversed negative voltage could possibly form, as determined by the negative calibration curve for the klydonograph. Furthermore, the negative figure definitely follows the previously formed positive striations showing that the residual positive space charge actually assists in the formation of the superimposed negative figure if the reversal occurs before the positive space charge ions have been dissipated by recombination. This phenomenon is shown by the Lichtenberg figures in Fig. 1 of the 1930 paper. Unfortunately this figure has lost much of the detail contained in the original films because of reproduction; however, this action can be seen even in the half-tone figure by careful observation.

The absence of small superimposed positive figures on the negative figures in Doctor Magnusson's paper is not surprising, because they frequently fail to develop and only appear under the most favorable conditions. This difference in the superimposed figures may be accounted for by the following theoretical considerations which appear to explain what happens fairly well. During the formation of the original positive figure the electrons and negative ions, which in general have small mass and high mobility, are swept by attraction toward the positive electrode and those reaching it are absorbed or neutralized by conduction. The positive ions resulting from ionization by collision in the striations around the electrode are massive and immobile and are repelled relatively very slowly by the electrode potential. When the electrode potential is quickly removed this positive ion space charge predominates, and the electrode becomes negative with respect to it, forming a small negative figure on the original positive when the applied voltage exceeds approximately twice the minimum figure forming voltage for the klydonograph. When the initial figure formed is negative instead of positive, the fast electrons and negative ions are swept outward away from the negative electrode leaving the relatively immobile positive ions, produced by ionization by collision in their wake, to be attracted toward the electrode. When the negative electrode potential is quickly removed, the residual space charges are very much nearer the same value than they were when the electrode was positive because of the low mobility of the attracted positive ions. Therefore, the mobile outer negative space charge is attracted into the immobile positive space charge surrounding the electrode when the repulsion of the electrode is decreased, and a large part of the ions constituting the two space charges are neutralized by recombination leaving only a very small residual negative space charge to reverse the gradient around the electrode. Therefore, the reversed Lichtenberg figure only forms over a negative figure under the most favorable conditions.

It has been shown conclusively by means of the cathode ray oscillograph that a conductor in corona at 60 cycles has around it a residual ion space charge large enough to initiate corona at zero conductor voltage when the applied voltage is slightly more than twice the visual critical corona voltage. If the applied voltage is increased to a value higher than this, corona is initiated by the residual ion space charge before the conductor potential reaches zero and, therefore, at a time when the conductor potential is in actual opposition to the corona formation. That is, during the normal rise and fall of potential in one-half cycle, both positive and negative corona are produced around the conductor in succession. (F. W. Peek, Jr., *Law of Corona and Dielectric Strength of Air IV*, TRANSACTIONS A.I.E.E., p. 1007, 1927. Lloyd and Starr *Corona Loss Measurements by Means of the Cathode Ray Oscillograph*, TRANSACTIONS A. I. E. E., 1927, p. 997.)

The formation of Lichtenberg figures is largely an ionization by collision or corona phenomena. The usual klydonograph or surge-voltage recorder for measuring voltage by the formation of Lichtenberg figures, is so constructed that from 3 to 5 kv will produce sufficient ionization to form figures. In the light of these known corona space charge phenomena, superimposed Lichtenberg figures would be expected to form at voltages slightly in excess of twice the minimum values required to record, and near the maximum rating or 30 kv the phenomenon should be quite pronounced.

**C. E. Magnusson:** Professor McMillan's discussion is greatly appreciated, particularly the part relating to the suggestion that polarity reversals in the electric figures may be caused by the space charges formed adjacent to the electrodes by the impulse discharge. The point raised by Professor McMillan can not be determined from the half-tone figures in the paper as the sharpness of definition and some of the details have been lost in the reproduction process, but on the original negative, Figs. 5 and 8, there are no indications of polarity reversal at either the positive or negative electrodes. On the negatives for Figs. 5 and 7 there may be very slight indications of reversal at the positive electrode with none at all at the negative electrode.

The author has examined a large number of the electric figure negatives and finds that in most cases polarity reversals are evident at both electrodes. In a number of cases polarity reversals are shown at only one electrode, either positive or negative, with no indication of reversal at the other electrode. However, in several negatives, including those for Figs. 5 and 8 in the paper, there are no indications of polarity reversal at either pole.

The cause of polarity reversals in the electric figures is very likely found in the oscillatory nature of most impulse discharges, either in a part reversal of the main impulse, or possibly in superimposed high frequency oscillations. Recently my colleague, Professor G. S. Smith, had considerable difficulty in locating the source of high frequency oscillations (65 million cycles) that appeared on a 1.5 microsecond impulse wave front. The oscillations were eliminated by properly shielding the lead-in wires, about 3 feet in length. Until recently very little attention has been given to the nature of the electric impulses used, whether oscillatory or unidirectional, in taking the electric or Lichtenberg figures.

# Probe Measurements and Potential Distribution
## in Copper A-C Arcs

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***Synopsis.****—A previous paper on a-c arcs in air between copper electrodes showed the influence of circuit constants in determining the rise of voltage across the electrodes during the reignition period of cyclic current zero. This paper gives the distribution of potential throughout the arc space between the electrodes during the reignition period, and shows that during that time the potential drop is concentrated largely in the space adjacent to the cathode, the major portion of the arc space is free from potential gradient, and the potential distribution is measurable with fidelity by means of inserted probes.*

### INTRODUCTION

SEVERAL articles of recent years have shown the importance of the problem of reignition of a-c arcs in air between copper electrodes.[1] Recently, two of the present authors described the conditions controlling the rate of voltage rise across the arc *electrodes* during the interval of cyclic current zero and its relation to the rate of deionization of the gap.[2] The arc reignites if the circuit constants permit the arc electrodes to experience a voltage rise of rapidity sufficient to overcome the growing dielectric strength of the arc space.

The present article shows the distribution of potential *between* the electrodes during the reignition period when the current is zero and emphasizes the possibilities and limitations of probe methods of measurement of this potential distribution.

One or more probes is introduced into the arc space, and by connecting one or another of the probes or the electrodes to a cathode ray oscillograph the changes in potential that take place in the arc space and near both electrodes during the reignition period are recorded.

The first outstanding result of the investigation is that, during the period when the arc current is passing through its cyclic zero and the electrode voltage is changing rapidly and reversing its polarity, the great percentage of the electrode voltage is to be found in a drop in potential at that electrode which is, for the time being, the cathode.

Furthermore, it appears that under appropriate conditions probe methods of measuring the rapidly changing potential distribution are justifiable.

### THE CIRCUIT AND THE ELECTRODE POTENTIAL

The circuit shown in Fig. 1, like that used in the earlier investigation,[2] comprises a 702-volt 60-cycle transformer connected to the arc electrodes through a contactor and an air core inductance of $L = 0.068$ henry whose distributed capacity is 610 $\mu\mu$f; $R = 1{,}000$ ohms is shunted across the arc electrodes to delay voltage recovery. The arc current of approximately 27 amps rms lags very nearly 90 degrees behind the transformer voltage. The electrodes are flat parallel-faced copper plates placed ¾ inch apart.

The arc is started by the burning of a No. 40 copper-wire fuse. The contactor is closed at the instant corresponding to zero steady-state current, thus avoiding a transient, and the arc is initiated when the fuse burns, about one-quarter cycle later. The cathode ray oscillograph records the electrode or probe-to-electrode voltage at the end of the second half-cycle of current.

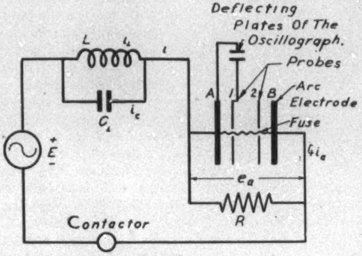

FIG. 1—THE CIRCUIT

$E$ = 992 volts = peak of 702-volt 60-cycle circuit voltage
$L$ = 0.068 henry
$C_L$ = 610 $\mu\mu$f
$R$ = 1,000 ohms
$i$ = 27 amp rms approximately
$e_a$ = $992 - 1{,}131\ \epsilon^{-0.0147t} + 64\ \epsilon^{-1.64t}$ volts. (Applicable during the reignition period only)
$t$ = microseconds after current zero

Except for the first few microseconds after current zero, the voltage across the electrodes rises according to the equation[2]

$$e_a = 992 - 1131\,\epsilon^{-0.0174\,t} + 64\,\epsilon^{-1.64\,t} \tag{1}$$

This is shown in Fig. 2 as a broken line; the heavy line is a replot of values taken from the oscillogram of Fig. 7A. A composite picture made from many oscillograms will check the broken line much more closely than the particular oscillogram shown in Fig. 2.

In the previous paper[2] it has been shown that for low values of resistance shunting the arc, the negative voltage dip does not follow the circuit equation, but that after a brief interval (in this case about 5 micro-

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1. For references see bibliography.

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seconds) the electrode voltage does follow the circuit equation developed from the circuit constants. At approximately 415 volts and 42 microseconds after "arc-failure" the arc space develops a glow discharge that lasts for 24 microseconds before the arc in the new direction begins. These values are typical, but of course there are variations from arc to arc in the magnitudes of the negative voltage dip, the reignition voltage, and the duration of the glow.

## PROBE MEASUREMENTS

The aims of these experiments have been to measure the distribution of the potential throughout the arc space during the period of current zero, and to show that this potential may be measured by the introduction of suitably shaped copper probes. The probes were thin copper plates placed between the electrodes, and had circular holes through which the arc might play. The probe finally adopted (Fig. 3) was made of sheet copper 1/64 inch thick, 1 inch square, with a hole 1/6 inch in diameter. The slot leading horizontally from the edge of the hole permitted insertion of the copper-wire fuse used to start the arc.

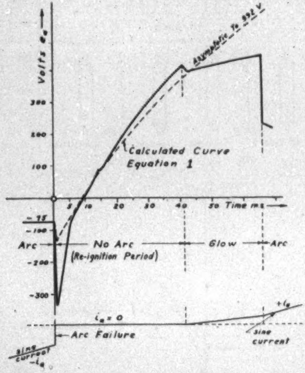

FIG. 2—VOLTAGE ACROSS ARC ELECTRODES. HEAVY LINE IS A PLOT OF OSCILLOGRAM OF FIG. 7A

Probes having hole diameters between 0.21 inch and 0.12 inch gave satisfactory and practically identical results. The sum of cathode-to-probe and probe-to-anode voltages equalled the cathode-to-anode voltage. Furthermore, the cathode-to-anode voltage gave the same record whether the probes were present or not. Probes with larger holes failed to measure the voltage, while with smaller holes the arc failed to restrike. Changes in overall dimensions of the probes had no effect upon the oscillographic records.

The simplest procedure in using a probe to measure a potential difference between an electrode and a point in an ionized gas is to connect the electrode and the probe to the two plates of a cathode ray oscillograph. As a first approximation it may be assumed that the oscillograph will respond faithfully to very rapid changes in potential without requiring the probe to draw any appreciable current from the ionized region in which it is placed.

A probe that does not carry current acquires a potential only approximately the same as that of the adjacent ionized gas. By measuring the small amounts of current drawn by probes at *controlled potentials* Langmuir determined the difference between a non-current-carrying probe's potential and that of the adjacent ionized gas in discharges at low pressures, and his method has been used by other experimenters[5,7,9] with arcs at atmospheric pressure.

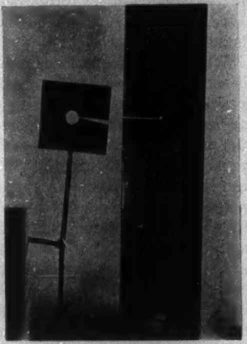

FIG. 3—PHOTOGRAPH OF PROBE AND ELECTRODE

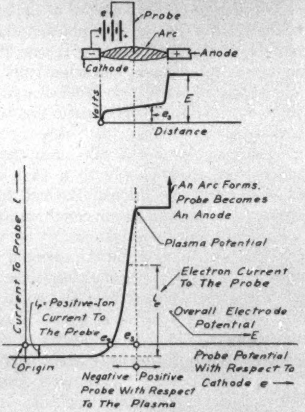
e
Probe
Arc
Anode
Cathode
Volts
E
$e_s$
Distance
Current To Probe $i$
An Arc Forms. Probe Becomes An Anode
Plasma Potential
Electron Current To The Probe
$i_e$
$i_p$ = Positive-Ion Current To The Probe
Overall Electrode Potential
E
$e_2$
$e_s$
Origin
Negative
Positive
Probe With Respect To The Plasma
Probe Potential With Respect To Cathode $e$

FIG. 4—VOLT-AMPERE CHARACTERISTIC OF A PROBE PLACED IN A STEADY DISCHARGE

The lower curve of Fig. 4 is typical of the volt-ampere characteristics of controlled-potential probes placed in what Langmuir terms "plasma" regions, which in general include all except the boundary regions of a great many arc and glow discharges. The cathode potential is considered zero, and $e_s$ is the potential in the gas of the discharge at the point where the probe is located; $e_0$, the potential of the probe when it is carrying no current, is measured by the cathode ray oscillograph. According to experiments by Nottingham,[5] Bramhall,[9] and Forbes[7] the difference of potential $e_s - e_0$ is of the order of 10 to 15 volts in a copper arc at atmospheric pressure. This is the error in measurement to be expected when using a probe which draws no current. When measuring potentials which run up into several hundred volts this error is negligible.

With a very low probe potential ($e < e_0$), the current is exceedingly small and consists entirely of a flow of positive ions from the ionized gas to the probe. Except at very low negative probe potentials, there is, besides the positive-ion current, an electron current flow to the probe in spite of its negative potential, because some of the electrons possessing higher energies overcome the potential difference between the plasma and the probe by virtue of the random motions of their thermal agitation. At $e = e_0$ this electron current is equal exactly to the positive-ion current, so that the net current to the probe is zero; if the probe potential is made higher the electron current rises rapidly. At $e = e_s$ the plasma and the probe have the same potential and there no longer is any hindrance to electron movement toward the probe.

A moderate rise in potential of the probe above that of the plasma ($e > e_s$) does not materially increase the number of electrons reaching it over the number that arrives due to random movement only, because of the appearance of a negative space-charge near the probe surface; hence the characteristic just to the right of $e_s$ is horizontal. When the probe potential becomes markedly higher (5 to 25 volts) than that of the plasma, the current rises sharply to a value determined by external circuit conditions. Beyond this point the arc strikes to the probe if circuit conditions permit.

Experimental investigations[5,7,9] of the copper d-c arc in air have shown that the essential theoretical conditions[6] for the existence of a plasma are fulfilled—*e.g.*, a relatively small electric field and equal concentrations of positive and negative charges. There is no reason for assuming that these conditions do not apply to the a-c arc. When the a-c arc current fails and the reignition period is reached the simplest assumption is that the arc space still contains a plasma but without any current flow. This assumption is borne out by overall voltage oscillograms of long arcs, 10 to 15 inch, taken during the reignition period, which show that during this time the overall voltage of a long ionized space substantially is that of a short space, indicating that the major portion of the ionized space is free from potential gradient—a condition that can prevail only if a plasma exists during the reignition period.

The probes used by the authors measure the potential at points outside the furthest radius of the arc-core proper and make them after current flow has ceased entirely. But studies[8] on dynamic a-c arc characteristics have shown that the establishment and decay of the arc-stream require considerable time, so that as the a-c current decreases from its maximum to zero the degree and extent of ionization persists over a much larger volume than that needed for the decreasing current flow. Further, unpublished work done by A. D. Forbes[7] under the direction of two of the authors indicates that the hot gases surrounding the arc-core fulfill the plasma conditions for a radial distance of several millimeters beyond the optically well-defined arc-core boundary, and that the potential of this surrounding plasma is lower than that of the arc-core itself only by a very few volts. The only reasonable conclusion is that the entire gaseous envelope is a persistent plasma region, hence probe measurements are valid during the reignition period.

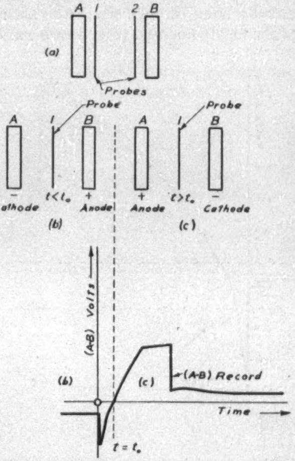

FIG. 5—POLARITIES OF PROBES AND ELECTRODES AT DIFFERENT INSTANTS

## DISTRIBUTION OF POTENTIAL THROUGH ARC SPACE

In the experiments first undertaken two probes were used, one placed near each electrode, as illustrated in Fig. 5a. Electrode $A$ served always as the "old cathode," hence also as the "new anode," the polarity change occurring at time $t = t_0$ of Fig. 5. The probe placed near the $A$ electrode was called No. 1, that near the $B$ electrode No. 2, and the measured voltages then identified as $(A - B)$, $(A - 1)$, $(A - 2)$ and $(2 - B)$. It was soon discovered that the probe-to-probe potential during the reignition period was very small, even with arcs of 10 inch and 15 inch length. With only very slight exceptions, the difference of potential between the electrodes is confined, during the reignition period, to thin regions adjacent to each electrode.

Therefore, in later experiments only one probe was used, placed half-way between the electrodes. With this arrangement the voltage oscillogram $(A - 1)$ reveals the potential changes adjacent to the surface of the $A$ electrode, and $(1 - B)$ that adjacent to the $B$ electrode. Figs. 5b and 5c illustrate the polarity relationships between the electrodes before and after time $t = t_0$.

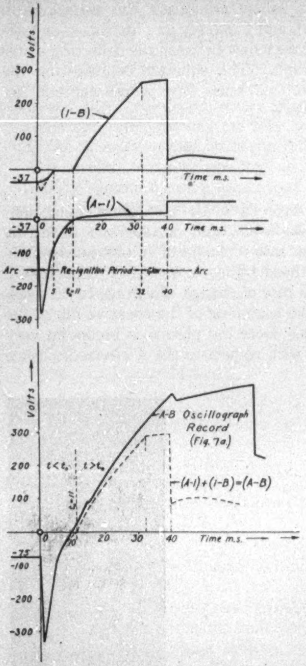

FIG. 6—POTENTIAL DISTRIBUTION THROUGH THE ARC SPACE

Fig. 6, drawn to scale, shows the potential drops $(A - 1)$ from electrode $A$ to probe, $(1 - B)$ from probe to electrode $B$, and the sum of these two voltages, $(A - 1) + (1 - B)$. This sum should equal the actual $(A - B)$ voltage, measured from electrode $A$ to electrode $B$, at every instant, and to illustrate the nature of this check, a typical $(A - B)$ oscillograph record is drawn on the same graph as the $(A - 1) + (1 - B)$ sum. It should be understood that the reignition voltage and the length of the glow period vary from arc to arc. The $(A - 1)$, $(1 - B)$ values and their sum $(A - 1) + (1 - B)$ are typical values taken from the study of many oscillograms, while the $(A - B)$ oscillograph record is the record of only one arc.

Prior to $t = 0$, (see Fig. 6) the arc current being negative, the $(A - 1)$ and $(1 - B)$ voltages are approximately 37 volts each, giving a 75-volt electrode drop $(A - B)$. At $t = 0$, the arc current drops from about 0.3 ampere to zero with extreme rapidity. From $t = 0$ to $t = 5$ microseconds the electrode voltage passes through a negative dip; most of this voltage is located in a thin layer adjacent to electrode $A$ which is, for the time being, the cathode. The probe-to-anode voltage $(1 - B)$ during this period may show a slight dip and then approach zero or may approach zero without any dip. At $t = 5$ the electrode voltage changes slope abruptly and thereafter follows closely the equation of circuit voltage rise (equation **1**). From $t = 5$ to $t = t_0 = 11$ microseconds, the electrode voltage is found almost entirely at the cathode $A$, the probe-to-anode potential $(1 - B)$ remaining nearly zero.

At $t = t_0 = 11$ the electrode voltage passes through its zero value. Thereafter $A$ is the anode and $B$ the cathode, and most of the voltage again is found at the cathode, though the anode drop appears to be of the order of 15 to 20 volts. At $t = 32$ the reignition period ends with the formation of a self-sustaining glow discharge during which the current increases slowly from zero in the positive direction. At $t = 40$ an arc is formed. The electrode and cathode voltages, $(A - B)$ and $(1 - B)$, drop rapidly while the current grows in a sinusoidal manner. In the change from glow to arc the anode voltage $(A - 1)$ may increase suddenly from 20 to about 50 volts.

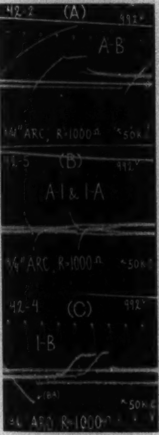

FIG. 7—POTENTIAL VARIATION WITH TIME

A. Across the electrodes
B. In the arc space near the $A$ electrode
C. In the arc space near the $B$ electrode

Figs. 7A, B and C are cathode ray oscillograms of the voltages $(A - B)$, $(A - 1)$ and $(1 - B)$. The two pairs of $(A - 1)$ voltages have been reversed with respect to each other in order to establish the position of the zero voltage line.

Fig. 8, derived from Fig. 6, represents the potential distribution in the arc region at various moments of time. It illustrates the absence during the reignition period of appreciable potential gradient except adjacent to the electrodes. A number of oscillograms under a variety of conditions were taken with two probes, one close to each electrode, in an attempt to discover a substantial potential gradient in the middle region when the voltage approaches reignition values, but so far the results have been entirely negative, even in the case of very long arcs failing to reignite. The oscillograms of Fig. 9 are selected to illustrate this fact. Fig. 9B is a cyclogram; horizontally it measures the voltage $(A - B)$ between the main electrodes, and vertically the voltage $(1 - 2)$ between the two probes. At no time except prior to current zero and after reignition does the voltage $(1 - 2)$ have any appreciable value.

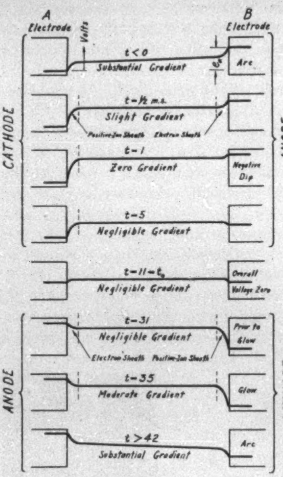

FIG. 8—POTENTIAL DISTRIBUTION THROUGH THE ARC SPACE

Fig. 9C measures horizontally the voltage $(A - B)$ and vertically the voltage $(2 - B)$. Following the negative voltage dip the trace is a 45-degree line, indicating that nearly all of the voltage drop in the arc region up to the moment of reignition occurs at the surface of the cathode. Figs. 9A and 9B both show that while the $(1 - 2)$ voltage is very small during the reignition period it grows to a considerable magnitude after the arc strikes.

These oscillograms show definitely that in the arcs used in these experiments the reignition process is one that is initiated in a thin layer of gas adjacent to the cathode surface. The variations in reignition voltage that have been observed in the authors' previous experiments therefore are a result of variation in the condition of a thin insulating layer of gas adjacent to the cathode.

## PROBE CURRENT REQUIREMENTS

It has been shown that the difference $(e_s - e_0)$ between the voltage acquired by the probe and that of the plasma is so small as to be of no consequence for the immediate purpose. To justify probe measurements it also is necessary to show that the current to the probe is sufficient to make the potential of the capacity represented by the leads and deflecting plates of the cathode ray oscillograph follow accurately the variations in plasma potential, and to supply any ionization or leakage current that may flow between the deflecting plates of the oscillograph. The equation representing the charging current that must flow to the cathode ray oscillograph plates is

$$i_p = C_p \frac{de}{dt}$$

where $C_p$ is the capacity of the measuring circuit consisting of probes, leads, and oscillograph deflecting plates, $de/dt$ is the rate of change of voltage between the plates, and $i_p$ is the charging current to the capacity $C_p$.

The maximum rate of change of voltage to be measured occurs at the beginning of the negative dip of the $(A - 1)$ pictures. Here the plasma is becoming very rapidly positive with respect to the $A$ electrode, hence to follow the change the probe must acquire a positive charge. This it can do only by means of the very small positive-ion current from the plasma; if the positive-ion current is too small relative to $C_p$ the oscillograph will not give an accurate record.

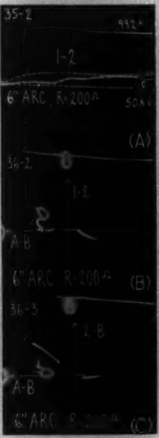

FIG. 9—POTENTIAL DROP ACROSS ARC SPACE

A. Across central arc space only. (See flat portion of curve near zero line)

B. Cyclogram of voltage of central arc space *vs* electrode voltage

C. Cyclogram of voltage of central arc space plus $B$ electrode drop *vs* electrode voltage

If it is assumed that during the negative dip the entire voltage appears between cathode and probe (this is the severest possible assumption) the rate of change of potential to which the probe must respond can be calculated as follows:

$$\frac{de}{dt} = \frac{I_1}{C_L} = \frac{0.3 \text{ (approximately)}}{610 \times 10^{-12}}$$

$$= 0.5 \times 10^9 \text{ volts per second} \quad (2)$$

The capacity $C_p$ used was not over 5 micromicrofarads. The 0.3-ampere figure used for $I_1$ is selected as the largest value of arc-failure current observed by the authors under similar conditions.[2] Using these figures the required charging current to the plates is

$$i_p = 0.5 \times 10^9 \times 5 \times 10^{-12} = 2.5 \times 10^{-3} \text{ amperes.} \quad (3)$$

Since the ionization current and the leakage current between the oscillograph plates of the high-vacuum oscillograph used probably are very much smaller than this, the capacity current is the controlling requirement.

The results of experiments by Nottingham[5] and by Bramhall[9] permit a rough estimate of positive-ion current density; values range from around 0.005 amp per sq cm at a distance of two millimeters from the center of an 8-ampere arc about one-half centimeter long to from 10 to 30 times that nearer the center of the core.

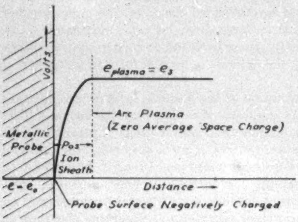

FIG. 10—POTENTIAL DISTRIBUTION THROUGH A POSITIVE-ION SHEATH

The arc used in the authors' reignition tests was nearly 2 centimeters long, and at its peak carried 38 amperes. It seems reasonable to expect that the positive-ion current density in the plasma that persists through the reignition period is at least 0.005 amp per sq cm and may substantially be larger. The area of the probe that is blackened by the heat of the arc indicates that the effective area of the probe in contact with the plasma may have been as large as 3 sq cm, whereas it need only be one-half sq cm to provide, at 0.005 amp per sq cm, the charging current required by the oscillograph under the most exacting conditions. Since these figures are very approximate, their chief value is to indicate that even at the beginning of the negative dip in the $(A - 1)$ picture the equipment used was working within the limit of accurate response.

The preceding discussion indicates only a reasonable probability that probe measurements should be successful. A necessary experimental check consists of tests to determine whether the voltage from cathode to probe plus that from probe to anode actually is equal to the voltage from cathode to anode. Tests of this kind were made on a variety of shapes and sizes of probes, leading finally to the choice of the probe shown in Fig. 3, which gave results that satisfied the experimental check required.

## ELECTRON MOVEMENT DURING REIGNITION PERIOD

The explanation for the potential distributions that are revealed by experiment is apparent if the probe-like nature of the electrode surfaces during the reignition period is recognized. After current zero and prior to reignition both electrodes are adjacent to a plasma region, yet little or no current passes from either of them to or from the plasma; the same statement applies to a probe placed between the electrodes. There is no essential difference then between electronic behavior in the boundary region adjacent to the probe and that adjacent to the main electrode surfaces. The lower part of Fig. 4 applies to the electrodes as well as to the probes during the reignition period. The potential distribution within the positive space-charge boundary region adjacent to either electrode or probe surface when negative with respect to the plasma has the general form represented by the curve of Fig. 10. The boundary region, which occupies a very thin layer of gas is called a positive-ion sheath because of the absence of electrons, which are kept out by the retarding field. The potential line is straight and horizontal in the probe and in the plasma, for in these regions there neither is potential gradient nor space-charge. The curvature of the potential line within the positive-ion-sheath indicates the presence of a positive space-charge density proportional to the rate of change of slope of the potential curve, the total positive space-charge being related closely to the overall sheath voltage.

Immediately after the arc current fails circuit conditions require an increase of overall arc voltage in the old direction; it reaches about 300 volts at $t = 1$. From Fig. 4 it is seen that if the potential of a probe-like surface adjacent to a plasma is raised to more than perhaps 20 volts above the plasma potential the probe becomes a new anode of the discharge, that is, it begins to draw electrons from the discharge at a substantial rate dependent upon circuit conditions. This circumstance limits the potential difference between the arc region and whichever of the two electrodes is positive with respect to it to something in the neighborhood of 20 volts.

Therefore, the cathode-to-probe drop must be 20 volts less than the overall potential $(A - B)$. Since during most of the reignition period the $(A - B)$ voltage is much greater than 20 volts, it follows that the great percentage of the $(A - B)$ voltage is to be found at the cathode, as is shown to be the case in Fig. 6.

During the period from $t = 0$ to $t = 1\mu$sec the overall voltage is rapidly increasing, hence the voltage drop $(A - 1)$ and its associated positive space-charge near the more negative electrode must increase very rapidly. (See the $t = 1/2$ graph of Fig. 8.) With a sufficiently rapid change in overall voltage the electron current flow taking place from the sheath at the cathode through the arc space to the anode and out into the metallic circuit may be comparable with the normal arc current in magnitude. During such a time the positive-ion sheath at the cathode may be thought of as a condenser that is being charged, except that the charge probably is not directly proportional to the difference of potential. There then is a slight potential gradient throughout the arc region, and a normal anode fall of potential at the more positive electrode, just as is the case when arc current in the ordinary sense is flowing.

By contrast the $t = 5$ graph of Fig. 8 illustrates the condition existing with a stationary or decreasing overall potential; this figure is strikingly similar to Fig. 3 of a recent article by Langmuir[6] illustrating the "trapping" of electrons in a plasma region containing a potential maximum.

### CONCLUSION

The authors feel that they have performed three tasks: first, to throw some light on the electronic activity that occurs during the reignition period of an a-c copper arc in air; second, to show that except adjacent to the electrodes the arc space possesses a negligible potential gradient during the reignition period; and third, to show that probe methods of measurement of the potential distribution are justified if the probes are used under conditions which do not violate the inherent limitations of the probe method.

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## Discussion

**J. Slepian:** This new application of the cathode ray oscillograph to the study of the potentials of probes in an alternating current arc, has led to interesting and valuable results. It shows quite definitely for short metallic arcs the development of the voltage bearing larger next to the cathode during the transition period. While this had been surmised before, it is very gratifying to see here a direct experimental confirmation of this important phenomenon.

The sudden change from an arc cathode to a glow type cathode prior to the current zero which the senior authors had discovered in their previous paper under the name "arc failure" is here again clearly revealed. It is an example of the development of insulating quality in the arc space before current zero is reached. Although at atmospheric pressure the voltage of the glow cathode is limited to a few hundred volts, at very low pressures this voltage may get very high. It is thought that this is the cause of high voltage that may appear in the high vacuum breaker when operated at a few amperes, and the writer also has observed high voltage surges in low current mercury arcs in inductive circuits which probably are due to this cause.

The curves of Fig. 8 permit one to set an upper limit to the time required for the formations of the voltage bearing cathode layer. The fact that the gradient in the positive column remained negligibly small from the moment of voltage reversal, $t = 11$ microseconds, until glow voltage was reached with the flow of measurable current, $t = 35$ microseconds, shows that the growth of the cathode layer was well able to keep pace with the developing voltage. It must be concluded then that the time required for the cathode layer to form must be small compared to 24 microseconds. Actually, there is reason to believe that if voltage is impressed quickly the cathode layer will form in a fraction of a microsecond.

The manner of formation of the cathode layer is well brought out in the paper. It supposes of course that the cathode itself is not a source of ionization until glow voltage is reached. This would not be the case, however, if refractory electrodes such as carbon or tungsten were used which could readily be raised to a temperature high enough for thermionic emission. For such electrodes quite different cathode layer characteristics should be expected. Have the authors taken any oscillograms of carbon or tungsten arcs? If so, what did they find?

**W. G. Dow, S. S. Attwood and G. S. Timoshenko:** The authors think that their work, particularly that given in an earlier paper,[1] shows that the cathode layer is built up to the point where it can withstand 350 volts in not over 2 microseconds, rather than in 24 microseconds as mentioned by Doctor Slepian. We wish to call particular attention to the peaked negative dip shown by the left-hand voltage record in Fig. 5c of the earlier paper. Here it appears that after "arc-failure," the negative cathode drop has become approximately 350 volts in not over 2 microseconds. There is no reason, in our opinion, to expect any difference in kind between the space charge sheath near the cathode in the negative direction and that established in the positive direction upon the reversal of arc electrode polarity.

Doctor Slepian has mentioned that our work indicates a "sudden change from an arc cathode to a glow type cathode prior to the current zero." He undoubtedly refers to the behavior typified by the left-hand voltage record in Fig. 5c of our previous paper. We do not believe his description fits the facts. The change here illustrated takes place in two distinct steps:

1. The arc current stops.
2. One-half to two microseconds later a glow discharge starts.

That these are two distinct independent steps is shown by the large number of records similar to the middle voltage record of Fig. 5c in which only the first step occurs, the negative voltage not increasing to a large enough value to permit the glow to start. We believe that the growth of space charge between these two events takes place in exactly the same way as its growth in the reverse direction a few microseconds later.

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[1] A.I.E.E. TRANS., Vol. 50, September 1931, p. 847.

In answer to Doctor Slepian's question, we have obtained a few oscillograms of the a-c carbon arc in air and found that there is no arc-failure and that the overall electrode voltage passes quite smoothly (much like a sine wave) through its polarity reversal. We think that this type of action is to be expected from a refractory material that has a very high melting or sublimation point. It may very well be that certain of the refractory materials can rise in temperature to the point where thermionic emission plays a role and that for these materials no true reignition period exists. We have not tried tungsten electrodes.

# Theory of Primary Networks

## Part I—A Study of Voltage Regulation and Load Distribution on Primary Networks

BY F. M. STARR*
Associate, A.I.E.E.

***Synopsis.***—*This paper presents solutions of practical operating problems of primary networks under normal and abnormal conditions. The general principles involved in network design are established. Charts are given which show in terms of elementary network data the load distribution in the network under various emergency conditions. Three simple equations involving only well known system constants are given which will enable the distribution engineer to determine the proper setting of the compensator and contact-making voltmeter to insure (1) that circulating currents shall be reduced to a minimum, (2) that overcompounding to secure proper voltage regulation shall be adequate, and (3) that any normal unbalance in load shall be reduced to a minimum. Other practical problems are discussed and answered.*

*An exact mathematical analysis of the general regulated network is given in the Appendix. This analysis is broad in scope and has evident applications other than the particular one with respect to primary networks as considered here.*

*The paper has been written to meet the requirements of operating engineers responsible for system networks. The results given here are substantiated by theoretical calculations, calculating board analyses and test data on actual systems in operation, and cover all practical conditions of steady state operation.*

*A subsequent paper will consider the primary network problems involved in short-circuit and relay studies.*

* * * * *

### INTRODUCTION

PREVIOUS literature on primary networks has been devoted largely to comparative economics. It is not the purpose of the present paper to re-discuss these factors but rather to consider the actual design and operation of the network itself. Part I of the paper is devoted to load distribution and voltage regulation, and Part II (to appear at a later date) will be concerned with short-circuit and relay studies.

The particular questions which it has seemed advisable to study in the present section of the paper are as follows:

1. When a transmission line feeding a primary network is taken out of service, how does the load carried by this line distribute among the network units remaining in service?

2. Quantitatively, what advantage in load distribution is gained by staggering the network loads on a given transmission feeder over concentrating adjacent loads on a given feeder?

3. What effect does the automatic regulating equipment (tap-changers or induction regulators) on the network transformers have on the distribution of load under normal and abnormal conditions?

4. Can the compensator used in conjunction with the regulating equipment be adjusted to limit circulating currents (due to differences in tap positions on the network transformers as well as to differences in the angles of the impressed primary voltages) to a desirable minimum, to aid in uniformly distributing a normally unbalanced load, and at the same time to give adequate over-compounding during peak load?

5. What maximum angular difference between supply voltages on the various primary feeders is permissible?

6. What procedure should be used in adjusting the compensator to give optimum performance?

These various factors have been studied analytically and by actual tests on networks in operation. In addition a number of calculating-board studies have been made. The conclusions arrived at here as a result of these studies, and the quantitative data obtained are thought to be quite reliable and should prove useful in the design and operation of primary networks.

As an aid to the analytical work in this paper, an exact mathematical analysis of the regulated network was developed, and is given in general form in the Appendix. Although this method of analysis is applied here to primary networks, it is perfectly general and should be useful in analyzing any network having a multiplicity of regulated feed points.

The material of this paper, as presented in the following pages consists of (1) a discussion of emergency load distribution with charts showing the distribution of load in a network under various emergency conditions, and with analyses showing the influence on emergency load distribution of such factors as automatic regulation, power factor, impedance of the 4-kv ties, etc., and (2) a discussion and analysis of normal network operation and design as influenced by such factors as voltage regulation, circulating currents, and unbalanced load.

### LOAD DISTRIBUTION UNDER EMERGENCY CONDITIONS

An important factor which affects the design of a primary network is the load distribution under conditions of both normal and emergency operation. It is desirable that the network be designed so as to permit all of the network transformers to share the load as uniformly as possible. No trouble usually is experienced in obtaining good load distribution under normal operat-

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ing conditions providing adequate 4-kv ties are incorporated in the design. In some rare cases where the load density is extremely light, it may be desirable to use high reactance transformers to insure uniform load division.

More important than the problem of normal load distribution in network design is that of emergency load distribution. In order that a primary network may be designed to have adequate reserve capacity under the emergency condition of a transmission line which feeds the network being out of service, it is necessary to know how the load carried by that feeder divides among the network units remaining in service.

A variety of networks differing in size and construction have been studied with this problem in mind, and in the light of these studies, the fundamental principles of emergency load distribution have been established. Primary networks may be very small, as for example those shown in Figs. 1A and 1B, or they may be quite large similar to that shown in Fig. 2. It is necessary to consider both the large and the small network to determine the limiting factors in load distribution.

Initially, networks are usually very small, only 3 or 4 units being tied together. The two networks shown in Figs. 1A and 1B are typical initial layouts and are very similar to 2 networks which are in operation at the present time. The network shown in Fig. 1A is a symmetrical layout of three units, each being supplied by a separate transmission feeder. If feeder 3 is taken out of service the load carried by unit 3 distributes uniformly between units 1 and 2 owing to the symmetry. Even though all of the 4-kv ties are not of equal impedance, the load division still will be fairly uniform if the units are all thoroughly tied together.

To illustrate this fact, load data on an actual network in operation are tabulated below:

| Feeder out | Load on $t_1$ | Load on $t_2$ | Load on $t_3$ |
|---|---|---|---|
| | 73 | 63 | 80 |
| A | 0 | 95 | 121 |
| B | 90 | 0 | 126 |
| C | 103 | 113 | 0 |

Above loads are in per cent of normal. The above data were taken on a network similar to Fig. 1A but with ties *e* and *f* open. The transformer reactances were 5.5 per cent, and the 4-kv ties had impedances as follows: $a = (4.54 + j2.56)$, $b = (3.64 + j2.06)$, $c = (4.15 + j1.87)$, and $d = (12.30 + j10.70)$.

The above table shows that in spite of the normal unbalance in load and the poorly linked network, fairly good emergency load distribution is obtained.

Now consider the network shown in Fig. 1B. This network of 4 units is fed by 2 lines, units 1 and 4 being supplied by feeder *A*, and units 2 and 3 being supplied by feeder *B*. If feeder *B* is out of service the load carried by units 2 and 3 will distribute uniformly between units 1 and 4 owing to the symmetrical layout. If each of the 4 points were fed by a separate line the emergency capacity of the network would be greater by the capacity of one unit than that of the layout as shown. Under this condition, if one of the units, say unit 4, were out of service, units 2 and 3 would each take approximately 35 per cent of its load and unit 1 would take the remaining 30 per cent (these values are based upon the assumption that the four internal ties are 4-per cent overhead lines, the four external ties are 7-per cent overhead lines, and the transformers have 6-per cent reactance).

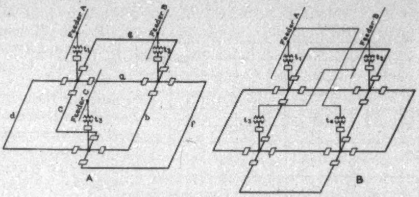

FIG. 1—TYPICAL SMALL-SIZED PRIMARY NETWORKS

These are characteristic of initial layouts
*A.* 3-unit network
*B.* 4-unit network

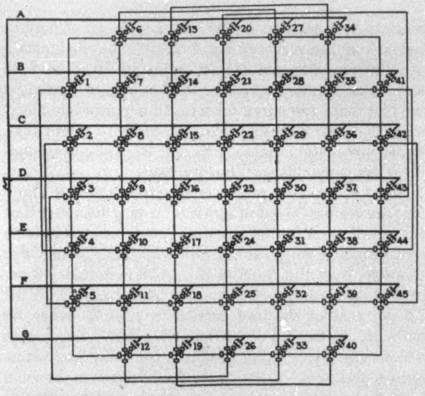

FIG. 2—TYPICAL LARGE-SIZED PRIMARY NETWORKS

This network was studied in regard to the various aspects of emergency load division

Experience has shown that networks of a size up to about 8 units may always be laid out in such a manner that the load carried by any feeder will distribute uniformly between the units remaining in service when that feeder is out of service. In larger networks the units adjacent to the transformers out of service will absorb more of the load than the more remote units. In order to determine the emergency load distribution in an extensive network, the layout shown in Fig. 2 was studied. An extensive calculating board study has been made on this particular layout, the results of part of which are shown in chart form in Figs. 3, 4, 5 and 6. By exercising some care, these results may be applied directly in designing any large sized network (assuming of course that the network is not too loosely tied together).

The curves of Fig. 3 show how a normal 100 per cent load carried by transformer 23 would distribute among the remaining units if transformer 23 were taken out of service. Thus, assuming the impedance of the network main to be 4 per cent (1,500 kva, 4-kv base), it may be noted from the curves of Fig. 3 that the 4 units immediately surrounding unit 23, *i.e.,* units 16, 22, 24 and 30, each take 7.3 per cent of the load originally carried by unit 23 (only the curve for unit 16 is plotted in Fig. 3 since the other 3 are identical to it owing to symmetry). Other units more remote from unit 23 take correspondingly less percentages of the total load.

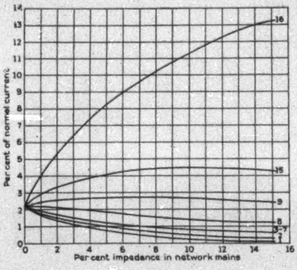

FIG. 3—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY UNIT 23 IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN 23 IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

Fig. 4 shows a set of curves similar to those of Fig. 3 for transformer 39 out of service. It may be noted that the distribution in this case does not differ greatly from that obtaining in the above case with unit 23 out. For example, from Fig. 4, units 32 and 38 each take 7.8 per cent of the load carried by unit 39 as compared with the 7.3 per cent of the load carried by unit 23 taken by units 16, 22, 24 and 30 in the above case. Space does not permit the printing of charts for other key transformer positions. However the 2 sets of curves shown in Figs. 3 and 4 represent the 2 extreme current distributions for any one transformer out of service, all other outages giving distributions intermediate to these. Therefore, it should be fairly easy to estimate emergency load distributions for any large network with reasonable accuracy from the data in charts of Figs. 3 and 4.

In a network of the size shown in Fig. 2, each transmission line would feed from 2 to 5 network units, the number depending on certain economic factors. In order to obtain the most uniform division of load under emergency conditions, it is desirable that the network units supplied by any one feeder be non-adjacent to each other, *i.e.,* staggered. For example, suppose units 11, 23 and 39 to be fed by a common feeder. If this feeder were taken out of service unit 24 would receive the most severe overload. In this case, again assuming 4 per cent network mains, unit 24 will receive 7.3 per cent of the load carried by unit 23 (from Fig. 3) and it will receive 1.8 per cent each of the loads carried by units 11 and 39. If each unit were normally loaded to 90 per cent of full load kilovoltampere, the emergency load on unit 24 will be approximately 0.9 (100 + 7.4 + 1.8 + 1.8) or 99.9 per cent of full-load kilovoltampere.*

A further examination of the data in Figs. 3 and 4 will demonstrate that the loss of a transmission feeder in a network of fairly large size need never impose an excessive overload on any transformer.

*Transmission Feeder Arrangement*

As pointed out above, the conventional method of feeding a network is to stagger the network units connected to any one feeder. For example, units 6, 22, 38 and 26 in Fig. 2 might be fed by one feeder, units 7, 23, 39 and 19 by another, etc. An alternative method would be to feed a group of adjacent network units from a single transmission line. The network in Fig. 2 is shown with this type of transmission layout. It is recognized that this sort of layout imposes a greater emergency overload burden on certain parts of the network when a transmission feeder goes out of service. However, it has been suggested that this latter method is more economical since the additional cost of interlacing the transmission lines more than balances the cost for the somewhat increased reserve transformer capacity required for the second arrangement.

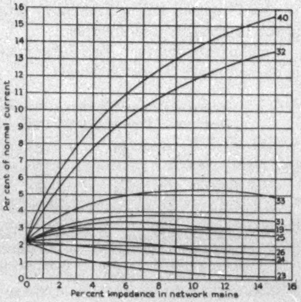

FIG. 4—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY UNIT 39 IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN 39 IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

In order to determine the probable maximum emergency overloads in networks whose feeders supply a series of adjacent units, the network of Fig. 2 was studied with the feeder arrangement as shown. The curves of Fig. 5 show the distribution of the load carried by feeder *A* when feeder *A* is out of service. Similarly the curves of Fig. 6 show the distribution for feeder *D* out of service (note that all loads are given in percentages of the normal load for any one transformer). It may be noted that the maximum overload on any unit for line *A* out of service (assuming 4 per cent impedance mains) is 31.5 per cent on unit 21 (see curve 21, Fig. 5), and for line *D* out of service it is 27 per cent on unit 24 (see curve 24, Fig. 6).

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*The error involved in superposing the several load components arithmetically to obtain the total is small and may be neglected.

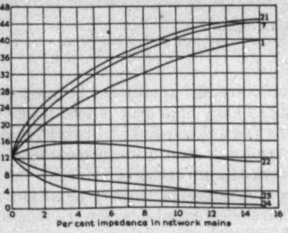

FIG. 5—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY FEEDER *A* IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN *A* IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

Since many utility engineers follow the practise of allowing 25 per cent or more short-time overloads on substation transformers under emergency conditions, it appears that the feeder arrangement shown in Fig. 2 may not be objectionable from the viewpoint of overloads and it may be highly desirable from the viewpoint of economy. Naturally the overloads on any particular transformer on a network considerably smaller than the one in Fig. 2 are apt to be greater, and more reserve transformer capacity will need to be provided. However, it should be borne in mind that, for small networks, this problem of feeder arrangement is not important since each of the units in a small network will be fed usually by a separate line.

### *Effect of Regulators on Emergency Load Division*

The foregoing studies and accompanying charts are the result of calculating board studies on fairly well-designed networks. In addition to these operating characteristics under optimum conditions, the relative effects on network operation of certain irregularities in design are important. It is important to know under what conditions the automatic regulators on the network transformers affect the emergency load division, to know quantitatively what this effect may be, and to know how this effect varies with power factor, impedance of the 4-kv ties, etc.

Voltage regulation on a primary network is maintained by means of automatic tap-changing equipment on the network transformer, or in some cases by means of induction regulators. In conjunction with a contact-making voltmeter and a line-drop compensator, these regulating equipments tend to hold 100 per cent voltage at some point in the secondary distribution system. The action of the regulator, in effect, is to change the magnitude of the voltage impressed on the transformer without affecting its phase angle. Furthermore, the operation of the contact-making voltmeter and compensator is to hold a constant magnitude of voltage at the load without regard to the angle of that voltage.

It is evident that this regulator action may in some cases influence the emergency load distribution in the network. The question may be asked, for example, if network unit 23 in Fig. 2 is taken out of service, what difference is there in the distribution of this load among the remaining units with and without automatic regulation? It may be shown (see below) that in closely-linked well designed networks the load distribution is substantially the same with or without regulation. It may be shown further that the greater the inherent unbalance due to the inherent impedance characteristics of the network, the greater will be the effect of the automatic regulators to change the distribution. Thus, if feeder *C* in Fig. 1A is out, its load will divide uniformly between units 1 and 2 whether regulators and compensators are provided or not. Similarly the emergency load distribution in the large network shown in Fig. 2 will not change much if the units are unregulated.

In order to study the effect of regulator action on emergency load distribution it was necessary to go to an extreme case in which this action was accentuated. For this purpose the simple three-unit network shown in elementary form in Fig. 7 was used. The impedance links *a* represent the network transformers and the connected transmission lines (the latter are usually negligible). The links *b* represent the 4-kv network mains or ties (in this case only a single tie between units is used in order to simulate the most extreme case of a loosely-linked network). The links *c* represent 100 per cent loads. The problem is to determine how the load normally carried by unit 3 divides between units 1 and 2 when unit 3 is out of service. To simplify the analysis the loads carried by units 1 and 2 have been omitted since their effects may be superposed later if desired. The method used is the exact analytical one developed in the Appendix. The calculated results for the various circuit conditions studied are tabulated in Table I. To simplify the analysis it was assumed that voltage magnitude was held at the bus rather than at some point

FIG. 6—THESE CURVES SHOW HOW THE LOAD NORMALLY CARRIED BY FEEDER *D* IN FIG. 2 DISTRIBUTES AMONG THE UNITS REMAINING IN SERVICE WHEN *D* IS OUT OF SERVICE

The transformer reactance used was 6 per cent. The percentage values are on a 1,500-kva, 4.3-kv base

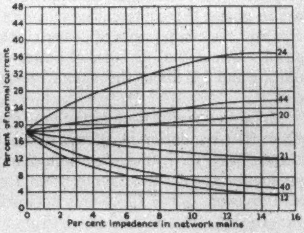

TABLE I

| No. | $a$ | $b$ | $c$ | $E_1$ | $E_2$ | $e_1$ | $e_2$ | $I_1$ | $I_2$ | $I_L$ | $I_1'$ | $I_2'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $0+j6$ | $5+j0$ | $95+j31$ | 108.45 | 93.54 | $100\underline{/-3.08^\circ}$ | $100\underline{/0^\circ}$ | 1.67 | 1.077 | 0.957 | 0.575 | 0.432 |
| 2 | $0+j6$ | $0+j5$ | $95+j31$ | 102.29 | 100.00 | $100\underline{/-2.02^\circ}$ | $100\underline{/-1.10^\circ}$ | 0.70 | 0.321 | 0.985 | 0.637 | 0.348 |
| 3 | $0+j6$ | $2.3+j5.1$ | $95+j31$ | 103.00 | 99.20 | $100\underline{/-2.05^\circ}$ | $100\underline{/-1.01^\circ}$ | 0.779 | 0.324 | 0.964 | 0.633 | 0.335 |
| 4 | $0+j6$ | $4.4+j1.4$ | $95+j31$ | 105.73 | 96.27 | $100\underline{/-2.41^\circ}$ | $100\underline{/-0.681^\circ}$ | 1.690 | 0.653 | 0.958 | 0.585 | 0.408 |
| 5 | $0+j6$ | $2.3+j5.1$ | $90+j43.6$ | 103.60 | 99.25 | $100\underline{/-1.92^\circ}$ | $100\underline{/-0.947^\circ}$ | 0.820 | 0.303 | 0.959 | 0.630 | 0.334 |
| 6 | $0+j6$ | $4.4+j1.4$ | $90+j43.6$ | 106.19 | 96.48 | $100\underline{/-2.27^\circ}$ | $100\underline{/-0.642^\circ}$ | 1.225 | 0.616 | 0.957 | 0.584 | 0.407 |
| 7 | $0+j6$ | $2.3+j5.1$ | $80+j60$ | 104.32 | 99.35 | $100\underline{/-1.68^\circ}$ | $100\underline{/-0.830^\circ}$ | 0.679 | 0.265 | 9.952 | 0.625 | 0.331 |
| 8 | $0+j6$ | $4.4+j1.4$ | $80+j60$ | 106.69 | 96.87 | $100\underline{/-2.02^\circ}$ | $100\underline{/-0.568^\circ}$ | 1.260 | 0.548 | 0.958 | 0.585 | 0.408 |

The above data apply to Fig. 7.
Impedance and voltage values are in per cent.
Current values are in times normal.
Currents $I_1$ and $I_2$ occur with regulation and $I_1'$ and $I_2'$ are the corresponding currents without regulation.
The network tie impedance, $(2.3+j5.1)$ is that of one mile of standard 4/0 overhead line; and the tie impedance, $(4.4+j1.4)$, is that of one mile of 1/0 underground 3-conductor cable.

near the load. Since the loads themselves do not change this assumption is legitimate for our present purpose.

From the data of Table I the following pertinent facts may be observed:

1. For highly reactive network ties, such as overhead lines, the distribution of load 3 between units 1 and 2 substantially is the same with and without regulation. This fact apparently is equally true for all reasonable load power factors. Since the network studied is an extremely loosely-linked one, it may be concluded from the above that the load distribution in all networks with overhead ties is not influenced greatly by the action of the regulators.

2. For highly resistive network ties, such as underground cables, the distribution of load 3 between units 1 and 2 is much more unbalanced with automatic regulation than without. This unbalance is less pronounced at lower load power factors.

3. The action of the regulators in cases 1, 4, 6 and 8 is to cause heavy circulating currents to flow from the adjacent unit to the remote unit as indicated by the magnitude of voltages $E_1$ and $E_2$. Since all of the $E$'s are in phase, these circulating currents are highly reactive and the components of power current are relatively small. The actual division of power currents between units 1 and 2 is about the same with or without regulation.

The above results demonstrate the maximum possible effect that regulation may have on load division. The network in Fig. 7, of course, would never be found in practise. The other extreme, from the standpoint of load division, is the three-unit network shown in Fig. 1A. In this case uniform load division under emergency conditions always will obtain and the regulators will have no effect whatever.

The quantitative criterion that determines the manner in which a load at a given point in a network (*i.e.*, the load on some transformer not in service) will distribute to the various points of feed is the range of variation in the transfer impedances from the point of load to the respective points of feed. A load at a given point will distribute directly as the transfer admittances to the various points of feed. In a closely-linked network the variation in transfer admittance between one pair of feed points and any other pair of feed points is small, which means that a closely-linked network insures a maximum uniformity in load division regardless of whether the network ties are cables or overhead lines. Furthermore, the differences in transfer admittances between feed points are less for a large network than for a small one (with the exception of certain symmetrical layouts), which indicates that a large network may have better operating characteristics from the standpoint of load division. It should be noted further that not only does the criterion of minimum differences in transfer admittances insure inherently a minimum of load unbalance, but this same criterion minimizes any tendency for the regulator action to set up circulating currents. To illustrate in a simple manner, refer to Fig. 7 and to case 4 in Table I. If the transfer admittances from the point of load $e_L$ to the two sources, $E_1$ and $E_2$, had been equal, not only would $I_1$ and $I_2$ have been equal, but their circulating components would have been zero.

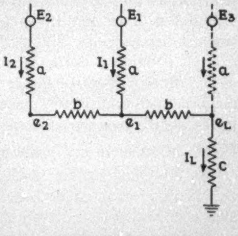

FIG. 7—THIS IMPEDANCE DIAGRAM REPRESENTS A SIMPLE 3-UNIT NETWORK WHICH WAS STUDIED TO DETERMINE THE FUNDAMENTAL EFFECTS OF BUS REGULATORS ON EMERGENCY LOAD DIVISION

The distribution of load $C$ between units 1 and 2 has been studied for various circuit constants. Refer to Table I

It may be stated in general that any effect which tends to improve load division under any emergency operating condition will also tend to limit circulating currents under the same condition.

The above conclusions are borne out in actual operating experience. In one particular case the transfer admittances between load points and various feed points do not differ by more than 10 per cent. Even though the network ties are highly resistive cables, the load carried by any transformer under normal conditions distributes practically uniformly when that transformer is out of service. The unit receiving the maximum portion of the redistributed load receives only 25 per cent more of this load than the unit receiving the minimum portion. Circulating currents are practicably negligible.

## NORMAL NETWORK OPERATION

The foregoing analysis and discussion have been confined to the design and operation of the network as affected by emergency operating conditions. The following discussion is concerned with normal network operation.

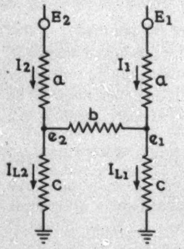

FIG. 8—THIS IMPEDANCE DIAGRAM REPRESENTS A SIMPLE 2-UNIT NETWORK WHICH WAS STUDIED TO DETERMINE THE EFFECT OF BUS REGULATORS ON A NORMALLY UNBALANCED LOAD

Optimum network performance requires that:

1. The regulators function to maintain approximately 100 per cent volts at some point in the secondary distribution system.
2. All circulating currents be reduced to a minimum.
3. The distribution of load in the network feeders be maintained as uniform as possible.

The chief instrument in operating the network to these requirements is the line-drop compensator. The following analysis will demonstrate how the compensator should be adjusted for various circuit constants to achieve these results.

### *Voltage Regulation*

Consider a single network unit, which may be designated as unit $k$, at any point in a network. The circuit constants associated with this unit are related by the following equations, which, though approximate, are, nevertheless, quite accurate and well suited to the present purpose. These relations are sufficiently well known as to require no proof. They are not vector but algebraic relations.

$$E_k = e_b + a_k I_t \sin \theta_t \qquad (1)$$

$$\beta = \frac{2I_t a_k \cos \theta_t}{e_b + E_k} \qquad (2)$$

$$e_b = I_L (R \cos \theta_L + X \sin \theta_L) + 100 \qquad (3)$$

$$e_{c.v.} = e_b - I_t (r \cos \theta_t - x \sin \theta_t) = 100 \qquad (4)$$

where

$E_k$ = voltage impressed on transformer $k$ in per cent.
$e_b$ = network unit bus voltage and reference vector.
$\beta$ = angle in radians between $E_k$ and $e_b$.
$a_k$ = transformer reactance in per cent.
$I_t$ = magnitude of transformer current in times normal.
$\theta_t$ = power factor angle of $I_t$ with respect to $e_b$.
$I_L$ = magnitude of load current in times normal.
$\theta_L$ = power factor angle of $I_L$ with respect to $e_b$. (Positive for lagging $I_L$ and negative for leading $I_L$.)
$e_{c.v.}$ = voltage impressed on contact-making voltmeter.
$r$ = resistance setting of the compensator.
$x$ = reactance setting of the compensator.
$R$ = apparent resistance in distribution system to load center.
$X$ = apparent reactance in distribution system to load center.

The vector relations of the above quantities are shown diagrammatically in Fig. 11. If there is no circulating current, $I_t = I_L$. Otherwise $I_t = I_L + I_C$ (vectorially), where $I_C$ is the circulating current from $E_k$ into the network owing to any cause whatever. Since voltages at the load center should be ideally 100 per cent, and since $e_{c.v.}$ is likewise 100 per cent, the following algebraic equation expressing the condition of perfect network regulation follows from equations (3) and (4) above:

$$(I_{CP} + I_{LP})\, r - (I_{CR} + I_{LR})\, x = I_{LP}R + I_{LR}X \qquad (5)$$

where the added subscript $P$ indicates power component of current, and the added subscript $R$ indicates reactive component of current (both referred to $e_b$). In equation (**5**), the reactive components of current are positive or negative accordingly as they are lagging or leading. If for any reason the left-hand member of this equation is less than the right-hand member, the voltage at the load will be too low.

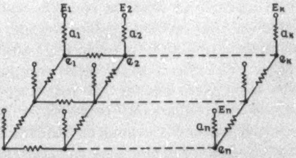

FIG. 9—THIS DIAGRAM REPRESENTS THE ELEMENTS OF THE GENERAL NETWORK HAVING $n$ REGULATED FEED POINTS

Refer to the Appendix for the general analysis

Equation (**5**) may be found particularly useful in determining the compensator setting best suited to good voltage regulation on the network. It is to be used on conjunction with equations (**6**) to (**9**) given below. Fig. 10 is a family of curves representing equation (**5**) for an assumed load current of 100 per cent, 0.95 power factor, and for $R$ = 3 per cent and $X$ = 7 per cent (all resistances and reactances being in per cent on a 1,500-kva, 4.3-kv base). These load and circuit constants were chosen because they are fairly representative of a large number of cases.

As stated above, if equation (**5**) is satisfied by the compensator settings, good regulation will result. Note, however, that, if 100 per cent voltage is held at full load, the voltage at light load will be somewhat less than 100 per cent owing to the decreased power factor that inherently accompanies a light load condition.

*Circulating Currents*

In regards to the functions of the compensator, next in importance to voltage regulation is the limitation of circulating currents. As is well known and as is evident from equations (**4**) and (**5**), this is accomplished by means of inverse reactance compensation. If any current flowing in the network unit transformer be resolved into power and reactive components, $I_P$ and $I_R$, the effect of that current on bus voltage, by virtue of the compensator action, is to add $rI_P$ and to subtract $xI_R$ volts. The effects of all other components of voltage are negligible. That is, the reactance compensation is effective in changing transformer taps only when reactive current is flowing, and the resistance compensation is effective in changing transformer taps only when power current is flowing. Since load current usually is of high power factor, the over-compounding during peak loads is determined chiefly by the amount of resistance compensation. Also, since circulating currents usually are highly reactive, their suppression depends chiefly on the amount of reactance compensation. Both power circulating currents and reactive circulating currents are discussed below.

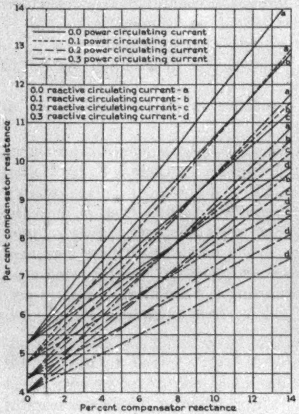

FIG. 10—THESE CURVES ARE USEFUL IN DETERMINING THE CORRECT COMPENSATOR SETTINGS TO MAINTAIN GOOD REGULATION ON A PRIMARY NETWORK FOR VARIOUS AMOUNTS OF POWER AND REACTIVE CIRCULATING CURRENT IN THE TRANSFORMER. A 100 PER CENT 0.95 POWER FACTOR LOAD WAS ASSUMED. CURRENTS ARE IN PER UNIT VALUES

Circulating currents due to differences in tap positions of the network transformer regulators always are highly reactive. If transformer $k$ has an impressed voltage $n$ taps above or below the voltage level of the network, and if each tap gives an increment change in $E_k$ of $\Delta E_k$, the circulating current into the network will be:

$$I_{CR} = \Delta E_k D_{kk} n \qquad (6)$$

where $D_{kk}$ is the driving point admittance (reciprocal of driving point impedance) from transformer $k$ into the network. Since $D_{kk}$ is highly reactive, $I_{CR}$ will be highly reactive and will tend to change the magnitude of $e_b$ by the amount, $\Delta E_k D_{kk} xn$, (a voltage increase if $I_{CR}$ is leading and a decrease if $I_{CR}$ is lagging). One tap change should not produce a change in bus voltage greater than the contact-making voltmeter voltage band in order that pumping and instability of the tap changers may be avoided, *i.e.*

$$\Delta E_k D_{kk} x < \text{C. V. Band } (\pm\ 0.5 \text{ per cent}) \qquad (7a)$$

Furthermore, 2 tap changes should produce a change in bus voltage greater than the contact-making voltmeter band to insure that reactive circulating currents shall be limited to a value not more than that corresponding to a single tap change, *i.e.*,

$$2\Delta E_k D_{kk} x > \text{C. V. Band} \qquad (7b)$$

Unlike circulating reactive currents, circulating power currents usually are caused by phase-angle differences in impressed transmission voltages. If $E_k$ is shifted $\delta°$ from the voltage level of the network, the times normal circulating current will be

$$I_{CP} = 1.75 D_{kk} \delta° \qquad (8)$$

This current, being an in-phase power current, will tend to produce a voltage change in $e_b$ of magnitude, 1.75 $rD_{kk}\delta°$. This change in voltage impressed on the contact-making voltmeter will cause a tap change which in turn causes a reactive circulating current to flow. This reactive current will prevent more than a single tap change from occuring due to phase-angle differences provided

$$\Delta E_k D_{kk} x > 1.75\, D_{kk} r \delta° \qquad (9)$$

The question arises as to how much circulating current owing to a difference in impressed-voltage phase-angle is permissible. This, of course, depends on the degree to which the network transformers are loaded. In general, a circulating current of from 0.10 to 0.15 of normal load current should not be objectionable. Since $D_{kk}$ varies from 0.12 in large networks to 0.065 in small networks (these values are the inverse of percentage driving point impedances, 1,500-kva, 4-kv base), in the average network, assuming a permissible circulating current of 0.15 of normal, the allowable phase shift of

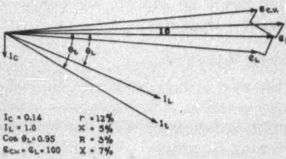

FIG. 11—VECTOR RELATIONS OF THE QUANTITIES DEFINED IN EQUATIONS (**1**) TO (**4**)

$E_k$ from the network voltage level should not be more than 1 deg.

Phase-angle differences in impressed voltages were determined on a particular network which is in operation. The maximum divergence from the average was found to be 0.98 deg at the time of full-load. The resulting power circulating currents were less than 0.10 of normal and not objectionable.

To illustrate the proper procedure in setting a network compensator, and to summarize the above analysis, the following example is given:

*Problem.* A network unit in a small-sized network is fed by a feeder whose voltage leads the network level by 0.5 deg. The driving point impedance from the transformer into the network is 9.2 per cent, or $D_{kk} = 1/9.2$. The contact-making voltmeter band is 1.0 per cent volts, and the regulator taps are 1.25 per cent volts each. What is the correct compensator setting?

From equation (**8**), the power circulating current due to 0.5 deg voltage phase displacement is 0.095 of normal. A reactive circulating current corresponding to 1 tap change (which is, from equation (**6**), 0.136 of normal in this case) should be assumed since the power circulating current is sufficient to cause at least one tap change. From equations (**7a**) and (**7b**) the compensator reactance $x$ should be less than 7.35 per cent and greater than 3.63 per cent. For a first trial, let $x = 6$ per cent. Then, (assuming average circuit conditions, *i.e.*, 0.95 power factor, $R = 3$ and $X = 7$) from equation (**5**) or from Fig. 10, the value of $r$ is found to be 7.4 per cent, which value fails to satisfy equation (**9**). However, if $x = 5$ per cent, $r = 6.9$ per cent, which value satisfies equations (**5**), (**7**) and (**9**) and is satisfactory.

### *Unbalanced Load*

It is highly desirable that a network have characteristics such that a normally unbalanced load will distribute uniformly among the various points of feed. The natural impedance characteristics of a network promote uniform distribution of load whether the network be regulated or not. This fact is borne out in the calculating board studies illustrated in Figs. 3, 4, 5 and 6.

In order to study the problem of distribution of unbalanced loads, the simple two-unit network shown in Fig. 8 was analyzed. The circuit constants and calculated data applying to this figure are summarized in Table II. It may be noted that two 0.95 power factor loads (load 1 being 10 per cent above normal and load 2 being 10 per cent below normal) were assumed. The distribution of loads was calculated assuming bus regulation (*i.e.*, $e_1 = e_2 = 100$), and then assuming no regulation at all at the network busses (this latter case being equivalent to regulation at the generating station). The layout was studied assuming the network tie to be a highly reactive overhead line (case 1), and assuming it to be a highly resistive underground cable (case 2). An examination of the data in Table II will substantiate the following facts and conclusions.

TABLE II

| Quantity measured | Case 1 | Case 2 |
|---|---|---|
| $a$ | $j6$ | $j6$ |
| $b$ | $2.3 + j5.1$ | $4.4 + j1.4$ |
| $c_1$ | $1.1\ (95 + j31)$ | $1.1\ (95 + j31)$ |
| $c_2$ | $0.9\ (95 + j31)$ | $0.9\ (95 + j31)$ |
| $E_1$ | 101.68 | 101.08 |
| $E_2$ | 102.85 | 103.40 |
| $e_1$ | $100.0\ \underline{/-3.12^\circ}$ | $100.0\ \underline{/-3.04^\circ}$ |
| $e_2$ | $100.0\ \underline{/-3.27^\circ}$ | $100.0\ \underline{/-3.35^\circ}$ |
| $I_1$ | $0.952\underline{/-17.2^\circ}$ | $0.902\underline{/-11.4^\circ}$ |
| $I_2$ | $1.063\underline{/-26.4^\circ}$ | $1.129\underline{/-30.2^\circ}$ |
| $I_1'$ | $0.982\underline{/-20.8^\circ}$ | $0.996\underline{/-19.8^\circ}$ |
| $I_2'$ | $1.028\underline{/-23.3^\circ}$ | $1.013\underline{/-23.8^\circ}$ |
| $I_{L1}$ | $0.910\underline{/-18.2^\circ}$ | $0.910\underline{/-18.2^\circ}$ |
| $I_{L2}$ | $1.100\underline{/-18.2^\circ}$ | $1.100\underline{/-18.2^\circ}$ |
| $I_L$ | $2.010\underline{/-18.2^\circ}$ | $2.010\underline{/-18.2^\circ}$ |

The above data apply to Fig. 8. Impedance and voltage values are in per cent. Current values are in times normal. Currents $I_1$, $I_2$ and $I_L$ occur with bus regulation, and currents $I_1'$ and $I_2'$ are the corresponding currents without regulation. The circuit constants are similar to those studied in Fig. 7, Table I.

The distribution of the load between the 2 network transformers is somewhat better without bus regulation than with, particularly so when the 4-kv tie is underground cable.

Thus, bus regulation alone, without compensation cannot be said to improve load division. However, suppose that compensation of the type described above be incorporated in the network units of Fig. 8. In case 1 in which the network tie is a highly reactive overhead line, a power circulating current flows from unit 1 which is underloaded to unit 2 which is overloaded. This power circulating current helps to balance up the load in the manner already indicated, but its effect on the compensator is to cause $E_1$ to increase and $E_2$ to decrease slightly, whereas the opposite effect is desired if a more equitable division of load is secured. Actually, the magnitude of the power circulating current in this case is so small that it would not result in any tap change at all.

Now consider case 2 in which the network tie is the highly resistive underground cable. Here the circulating current is highly reactive. This reactive current, in itself, has little effect in balancing up the load. However, its action on the compensator, in contrast with the corresponding action of case 1, is to cause $E_2$ to increase and $E_1$ to decrease, which action has a beneficial effect in balancing up the loads. It should be noted furthermore, that, whereas the circulating current in case 1 is small in magnitude, the circulating current in case 2, on the other hand, is of appreciable magnitude and will result in an actual change of taps.

The above analysis leads to the conclusion, then, that for networks inherently endowed with unbalanced loads, the resistance compensation should be somewhat smaller when the ties are overhead lines than when they are cables. Networks having overhead ties have a greater inherent tendency to balance loads than do networks with cable ties. Networks with cable ties, on the other hand, are able better to improve load division by virtue of the effect of the inverse reactance compensation.

## Appendix

*Analysis of the Regulated Network*

Fig. 9 is a simplified impedance diagram of a primary network that is intended to represent any network having $n$ points of feed. The transformers feeding the grid are represented by impedances $a_1$, $a_2$, etc. These transformer impedance links are intended to include the impedances of the transmission lines feeding them, which however usually are negligible. The $E$'s are the voltages impressed on the various transformers, and their magnitudes will vary from 100 per cent depending on the tap positions of their respective load ratio control equipments. The $e$'s are the bus voltages of the respective network units. It will be assumed here that the $E$'s are all in phase, and that the $e$'s are all equal in magnitude and equal to some value, say 100 per cent volts. Loads are not shown in Fig. 9 since the following analysis applies without respect to the manner in which the network is loaded.

The currents flowing into the general network of Fig. 9 at the various points of feed will be:

$$\begin{array}{l} I_1 = D_{11}E_1 + D_{12}E_2 + \ldots + D_{1n}E_n \\ I_2 = D_{21}E_1 + D_{22}E_2 + \ldots + D_{2n}E_n \\ \vdots \\ I_n = D_{n1}E_1 + D_{n2}E_2 + \ldots + D_{nn}E_n \end{array} \qquad (10)$$

where $D_{11}, D_{22} \ldots D_{nn}$ are the driving point admittances from feed points $1, 2 \ldots n$ respectively, and coefficients of the form $D_{jk}$ are transfer admittances (between points $j$ and $k$). These coefficients are the characteristic admittances of the network and may be determined readily by measurement or calculation.*

In addition to equation (**10**) the following vector relations are evident:

$$\begin{array}{l} e_1 + a_1I_1 = E_1 \\ e_2 + a_2I_2 = E_2 \\ \vdots \\ e_n + a_nI_n = E_n \end{array} \qquad (11)$$

In addition to equations (**10**) and (**11**) the conditions of the problem specify that all of the $E$'s are in phase but of unknown magnitude, and that all of the $e$'s are equal to 100 per cent volts but of unknown phase angle.

If in equation (**10**) above the $j$'th equation be multiplied through by $a_j$, and the $k$'th equation be multiplied through by $a_k$, and so on, and then if the term $a_kI_k$ on the left of each equation be replaced by $E_k - e_k$, there results:

$$\begin{array}{l} -e_1 = (D_{11}a_1 - 1)E_1 + (D_{12}a_1)E_2 + \ldots + (D_{1n}a_1)E_n \\ -e_2 = (D_{21}a_2)E_1 + (D_{22}a_2 - 1)E_2 + \ldots + (D_{2n}a_2)E_n \\ \vdots \\ -e_n = (D_{n1}a_n)E_1 + (D_{n2}a_n)E_2 + \ldots + (D_{nn}a_n - 1)E_n \end{array} \qquad (12)$$

Let equation (**12**) be written as:

$$\begin{array}{l} D_{11}'E_1 + D_{12}'E_2 + \ldots D_{1n}'E_n = e_1 \\ D_{21}'E_1 + D_{22}'E_2 + \ldots D_{2n}'E_n = e_2 \\ \vdots \\ D_{n1}'E_1 + D_{n2}'E_2 + \ldots D_{nn}'E_n = e_n \end{array} \qquad (13)$$

Let the real and imaginary components of the $D'$ coefficients be $D_{jk}' = m_{jk} + jn_{jk}$. Since all of the $E$'s are in phase the following algebraic relations may be written:

$$\begin{array}{l} m_{11}E_1 + m_{12}E_2 + \ldots + m_{1n}E_n = R(e_1) \\ m_{21}E_1 + m_{22}E_2 + \ldots + m_{2n}E_n = R(e_2) \\ \vdots \\ m_{n1}E_1 + m_{n2}E_2 + \ldots + m_{nn}E_n = R(e_n) \end{array} \qquad (14)$$

where $R(e_k)$ is the real part of $e_k$ (using $E$ as the reference vector). Since $e_k = E_k - a_kI_k$, and since $a_kI_k$ is never greater than $0.07e_k$, it follows that $R(e_k)$ will differ from the magnitude of $e_k$ by not more than $0.002e_k$, and it is therefore proper to replace the right-hand members of equation (**14**) by $e$. Equation (**14**) may be solved readily for the $E$'s by means of determinants or a simple calculating board set-up. Then the $I$'s may be determined from equation (**10**).

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## Discussion

**Leonard M. Olmsted:** The design of any network should provide sufficient capacity in excess of normal load requirements to carry, without exceeding the permissible overload capacity of any transformer, the additional load imposed upon the remaining transformers when a certain number of transmission circuits is out of service. This number is determined by the total number of circuits supplying the network, by the policy governing times during which circuits are de-energized for routine work, and by previous experience with network feeder outages. This

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*Refer to *Equivalent Circuits—I*, TRANS. A.I.E.E., Vol. 51, June 1932, p. 287.

emergency loading is a function of the total amount of load normally carried on the transformers out of service, the location of these transformers in the network, and the relative impedances of the network mains and transformers.

Cognizance of the importance of proper emergency capacity for satisfactory operation of network systems led us, some 16 months ago, to initiate an extensive calculating board analysis. Since out network differs from Mr. Starr's only in the inclusion of 4 more transformers located one at each corner of the network, and the omission of the long ties shown in Fig. 2 of his paper as 6-27, 13-34, 20-43, etc., it is reasonable to compare the results. Our methods of analysis are too dissimilar to permit direct comparison for interlaced transmission, but we have handled the parallel transmission in exactly identical manner and accordingly these results will be studied.

For 4-kv mains between adjacent transformers and the transformers each of 6 per cent impedance, with circuit *D* out of service, our analysis shows that each transformer on circuits *C* and *E* picks up 32 per cent of the load dropped by one of the transformers on *D*. Since Mr. Starr has additional ties to improve the distribution, his figure of 30 per cent for transformer No. 24 must be considered a close check.

A network must be designed, however, to withstand the most extreme reasonable load distribution, which is represented in our study by circuit *A* being out. For this case, transformers on circuit *B* pick up 62 per cent of the load dropped by circuit *A*. In the paper, however, the corresponding outage causes maximum increase in load of 35.5 per cent. Such decided improvement in the emergency load distribution suggests that the seemingly slight differences between the two layouts are actually of considerable importance. Accordingly, Mr. Starr's network has studied for 6 per cent impedance transformers and mains, with interesting results.

The first set up had exactly the same arrangement of circuits as shown in Fig. 2 of the paper. It was assumed that the 4-kv circuits are all of the same type of construction and would therefor have impedances proportional to the distances. Thus 6-13, 13-20, 20-21, etc., would all be 6 per cent, 1-6, 34-41, 5-12, and 40-45 would be 12 per cent; 6-27, 13-34, 1-4, 2-5, 12-33, 19-40, 41-44 and 42-45 would be at least 18 per cent, and the long ties 20-43 and 3-26 would be 36 per cent impedance. Using these impedances, with circuit *A* dead the percentages of normal current corresponding to those shown in Fig. 5 for 6 per cent impedance in network mains become as follows:

No. 21—47%, No. 7—42%, No. 1—30%.
No. 22—18%, No. 23— 7%, No. 24— 4%.

The numbers refer to the transformer locations shown in Fig. 2 of the paper.

If the long ties are shortened by 29.3 per cent to represent the diagonal distance, the percentages of normal current become:

No. 21—46%, No. 7—42%, No. 1—30%.
No. 22—18%, No. 23— 6%, No. 24— 3%.

In order to check the published figures, it was necessary to reduce all impedances, including 1-6, 34-41, etc., 6-27, 13-34, etc., and the long ties 20-43 and 3-26 all to 6 per cent. It is exceedingly difficult to perceive how such reductions could be accomplished in practice, but the following results clearly indicate that such was the basis for the paper:

No. 21—36%, No. 7—35%, No. 1—30%.
No. 22—14%, No. 23— 7%, No. 24— 4%.

Having demonstrated that with reasonable impedances 47 per cent, or at least 46 per cent, is the maximum load transferred to an adjacent transformer when circuit *A* is de-energized, it is next pertinent to ascertain the reduction in loading attributable to the ties 6-27, 13-34, etc., and 20-43, and 3-26. With these ties open, the load on No. 21 is 51 per cent, thereby indicating reduction of 4 to 5 per cent for practical values of impedance in the ties.

Without the above ties, the network differs from ours only by the omission of one transformer at each end of circuits *A* and *G*. This reduces the load dropped by circuit *A* by 28.6 per cent, and thus reduces the additional burden thrown upon circuit *B*. At the same time, however, the capacity on circuit *A* available to carry load when circuit *B* is de-energized, has been reduced by 28.6 per cent and it is pertinent to investigate whether the loadings may not be greater than that thrown on transformer No. 24 when circuit *A* is out, which the casual reader of the paper would infer to represent the worst condition. Considering first the system layout that gave loadings in accordance with Fig. 5 of the paper, it is found that No. 6, No. 13, and No. 20 pick up 49 per cent, 45 per cent, and 40 per cent, respectively, all of which exceed the 35.5 per cent shown in Fig. 5. Similarly with reasonable values of impedance in the longer tie circuits the loading on No. 6 is 52 per cent; without the ties, the loading becomes 59 per cent.

From the above disclosures, it is concluded that the paper does not show the worst loadings for parallel transmission even for the network constants upon which it would seem to be based. Furthermore, it seems impractical to install the circuits of from 3 to 6 times the length of the ties between adjacent transformers to have the same impedance as the shorter connections. In fact the writer is of the opinion that it is more practical to eliminate the tie circuits outside the square network entirely, in their place installing 4 more transformers located one at each corner of the mesh. It is believed that this change entails little, if any, increase in system investment, provides more satisfactory operating characteristics, and can be so loaded as to increase the load capacity of the entire network.

**M. S. Schneider:** The three-phase 120-208-volt network in Cincinnati is supplied by four 13.2-kv circuits. Three of these have induction regulators with standard control and compensators. The compensators were first set to correspond to the circuit resistance—reactance ratio or approximately 1 to 10. This resulted in circulating rkva, which, of course, caused one regulator to "boost" and the other to "buck" still more, with the final result that unbalanced voltage and loading existed on the circuits.

In order to improve conditions, the resistance—reactance ratio was changed to 10 to 1 approximately. The result is that the regulators are now affected almost entirely by the kilowatt load which does not change appreciably with a voltage change on one circuit. This naturally stabilized their operation and improved the voltage conditions as well as the loading.

The following tabulation shows this improvement:

| | Volts | | | Circulating rkva |
|---|---|---|---|---|
| | Maximum | Minimum | Difference | |
| Before change in compensation | 131 | 125 | 6 | 575 |
| After change in compensation | 129 | 127 | 2 | 200 |

Reversed compensation has not been necessary. However, there is some thought of increasing voltage during heavy load and in that event slight negative reactance compensation will be used.

**F. M. Starr:** Mr. Olmsted has presumably misinterpreted the significance of the network shown in Fig. 2. It was intended in this layout to simulate an infinite network so far as the internal operation of the network is concerned. This procedure was necessary in order to establish general principles of network emergency operation. It should not be construed, therefore, that the network of Fig. 2 represents an actual physical layout.

As Mr. Olmsted has stated, an actual layout would not have ties 6-27, 13-34, 20-43, etc., connected as shown. However, it always is possible to arrange a network with 4 ties of low impedance emanating from each unit. Such a layout will give results entirely similar to those indicated in Figs. 3, 4, 5 and 6. The author has made numerous load studies on a great variety of actual network layouts and has found that it is invariably possible to limit emergency overloads to a maximum of about 40 per cent.

Mr. Olmsted has shown that, by putting network units in the corners of the layout as shown in Fig. 2 and by increasing the impedances of some of the ties, a greater load unbalance can be obtained. This is absolutely true and proves absolutely nothing. Obviously a unit tied into the network with only 2 ties is going to overload the 2 adjacent units excessively when it is out of service. But it is never necessary to design a network in any such fashion, and the overloads existent with such conditions may always be avoided.

Mr. M. S. Schneider has presented some interesting results demonstrating the reduction in circulating currents which can be obtained by going to high-resistance compensation. He accomplishes approximately the same result by using high-resistance compensation and a relatively low-reactance compensation as is accomplished in the primary network by using negative reactance compensation. Where considerable over-compounding at the unit bus is required to hold voltage at the load, it will be found necessary to use some negative reactance compensation with a fairly high-resistance compensation to avoid reactive circulating currents.

# Transient Torques in Synchronous Machines

BY M. STONE* and L. A. KILGORE†

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***Synopsis.**—The calculation of the alternating torque developed on single-phase short circuit has been discussed by previous authors.[1,7] This paper extends the analysis of the electrical torque on short circuit to cover the transient torques due to losses, which although not so large as the alternating torques may be the most serious factor in the effects of short-circuit torques.*

*The resulting mechanical torques in the various parts of the machine are analyzed, and some important conclusions reached: (1) That a rigid stator transmits all the electrical torque developed; while the shaft and coupling of a coupled set, or the springs in a spring-mounted stator in general need transmit only a fraction of the alternating components. The greater part of the alternating components of the electrical torque are absorbed by the inertias involved, when the natural frequency of torsional oscillation is below the rated frequency. This is the case always for spring-mounted stators, and almost always the case for coupled rotors.*

*(2) That the sudden increase in torque on short-circuit conditions determined by losses in the negative sequence resistance (mainly the rotor losses) or in the resistance of the external circuit, may produce higher mechanical torques in shafts and couplings than the alternating components of the electrical torque.*

*(3) That there are other transient conditions which may produce more serious mechanical torques than sudden short circuit. These are: (1) synchronizing out of phase, (2) allowing a machine to pull out of step and remain connected to the system until the slip frequency approaches the natural frequency of torsional oscillation.*

## General Discussion

It has long been known that very high values of alternating torques are developed on sudden short circuit. One of the early incidents that revealed the magnitude of such forces occurred when the holding down bolts of the first large generators for Niagara were sheared off due to a short circuit. There have been very few failures in recent years because adequate allowance for these forces are made in design. A number of excellent papers[1,7,9] have been written on the calculation and measurement of the alternating components of electrical short-circuit torque. Very little has been published, however, concerning the mechanical effects of transient torques.

In this paper, the resulting mechanical torques in the various parts of the machine are analyzed for the different components of transient electrical torque. The analysis of the electrical torque is extended to include the initial torques due to losses, which are found to be relatively important. Other transient conditions that may produce more serious torques are discussed. The general discussion and simplified calculations are given first, since these are of most general interest.

## Discussion of Results

The electrical torques developed on sudden short circuit may be resolved into alternating components and loss components. The alternating torque consists mainly of a rated frequency torque due to the reaction of the flux with the asymmetrical armature current, and the double frequency torque due to the alternating current. The loss torque is due mainly to losses in the negative phase sequence resistance of the machine and in the external resistance, if any. The peak value of the electrical torque is limited chiefly by the subtransient reactance ($x_d''$) although for machines without damper windings, the difference between the direct and quadrature axis reactances ($x_d'' - x_q''$) increases the peak torque.

Typical values of peak electrical torques for the several types of synchronous machines (expressed in number of times the "unit torque," corresponding to rated speed with a kilowatt load equal to the rated kilovoltampere) are as follows: salient pole machines, 6; 1,800-rpm turbine generators, 10; and 3,600-rpm turbine generators, 14.

Concerning the mechanical effects: the total electrical torques developed are considered to be transmitted undiminished through a rigid stator—but it is relatively easy to design a stator to carry this peak torque. However, for the shaft and coupling between mechanically coupled rotors, the peak mechanical torque fortunately is almost always reduced considerably, since the greater part of the electrical torque developed is absorbed by the inertia of the rotors. (The term "mechanical torque" is used here to distinguish it from the electrical torque developed.)

The quantitative effect of the inertias of the coupled rotors and the spring action of the shaft in reducing the effective torque is shown by equation (4). It may be seen that where the natural period of torsional oscillation is below the rated frequency (as is the case almost always) the alternating components are greatly reduced. The ratio of the inertia of the coupled rotor to the sum of the inertias, $(I_1)/(I_1 + I_2)$ also enters in the reduction of shaft torques. Calculations on typical large machines of each type showed values of per unit peak shaft torque due to single-phase short circuit from no-load to be less than 0.5 for waterwheel machines and 2.0 for turbine generators. The transient torque in waterwheel shafts are particularly low due to the low inertias of water turbines. While these figures are for typical machines, individual machines may vary considerably because of the possible variations in natural frequency.

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1. For references see bibliography.

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The springs of a spring-mounted single-phase machine, do not transmit much of the alternating torque. There is no reduction due to a ratio of inertias, since the foundation is considered rigid, giving in effect an infinite inertia; but the natural frequency is always kept well below the rated frequency. An example of test and calculated curves for this case is given in Fig. 1. The spring torque was determined by recording the instantaneous spring deflections on a vibrograph. The inertia torque of the stator was also measured by use of a hydraulic accelerometer.

The mechanical analysis leads to another important conclusion: that there are other possible transient conditions which may produce more severe mechanical torques than sudden short circuits. These conditions are (1) synchronizing out of phase, and (2) allowing a machine to pull out of step and remain on the system until the slip frequency approaches the natural frequency of torsional oscillation. Transient torques due to system power oscillations, in which the machine does not pull out of step, generally do not produce serious torques because the oscillation frequency always is lower than the natural frequency.

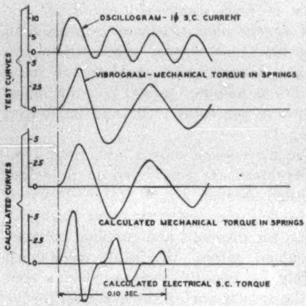

FIG. 1—CURVES OF CALCULATED AND MEASURED SHORT-CIRCUIT TORQUES

It is, of course, well known that throwing a machine on a large system out of phase by more than 60 deg produces a worse electrical transient than sudden short circuit; this analysis shows that even with a 30 deg angle, a low reactance machine (such as a 3,600-rpm turbine generator) will have a suddenly applied average electrical torque of about four times normal in addition to the alternating components, and may produce more serious mechanical effects.

The transient associated with a machine pulling out of step produces no very serious torques unless the machine is allowed to remain on the system until the slip frequency approaches the natural frequency of torsional oscillation. This slip will generally be of the order of 10 per cent or higher. The slip frequency electrical torque developed under this condition will not be much greater than rated torque, but as the resonant frequency is approached, the mechanical torques are limited only by the mechanical damping and the speed of passing through resonance. Very high mechanical torques are possible and this condition should always be avoided.

## SIMPLIFIED CALCULATION OF ELECTRICAL AND MECHANICAL SHORT-CIRCUIT TORQUES

As stated previously, a rigid stator frame transmits the peak electrical torque developed—the complete equation for the instantaneous torque being given by equations (**5**) and (**9**). A simple, but useful, approximate expression for the peak torque on single-phase short circuit, neglecting decrements and losses, may be used (the symbols being as defined at the end of this section):

$$T_p \simeq \frac{2.6\, e_0^2}{x_2 + x_d''}\left[1 + 17\left(\frac{x_2 - x_d''}{x_2 + x_d''}\right)^2\right] \quad (1)$$

For a short circuit at the terminals, the loss component does not add much to the peak and it is offset approximately by the neglected decrement effects. Where the external resistance is appreciable, the initial asymmetrical loss torque, $T_3$ (as defined in equation (**3**) ), should be added.

For the case of coupled rotors, the peak mechanical torques in the shaft or coupling can be determined by plotting the simplified formula, equation (**4**) for one cycle. This simplified formula was derived neglecting all decrement, but an approximate factor may be applied to peak torque to take this into account; calculations based on the more complete analysis (equation (**17**) ), show this factor to be about 0.9 to 0.8 for most normal machines. Cases approaching resonance are treated in the latter part of this paper including both the mechanical and electrical decrement; it is sufficient to emphasize here that resonance should always be avoided.

Certain other justifiable assumptions are made to simplify the results. The effect of resistance in limiting the current and the average change in speed are neglected. The effect of the higher harmonics (above the second) are also neglected. The short circuit is assumed to occur at the instant of maximum interlinkage, since this gives the maximum electrical torque. The formula is derived for a short circuit from no load which gives the greatest sudden increase in average torque and hence almost always would give the highest peak shaft torque.

Based on the assumptions stated above, the per unit electrical torque ($T_{el}$) may be written for a single-phase short circuit as:

$$T_{el} = T_1 \sin \omega t - T_2 \sin 2\omega t$$
$$+ T_3\left[1 - \frac{4}{3}\cos \omega t + \frac{1}{3}\cos 2\omega t\right] \quad (2)$$

For a line-to-line short circuit:

$$T_1 = \frac{2e_0^2}{x_2 + x_d''}$$

$$T_2 = \frac{2e_0^2}{x_2 + x_d''}\left[\frac{x_2}{x_2 + x_d''} + \frac{x_2 - x_d''}{x_2}\right]$$

$$\approx \frac{T_1}{2} \text{ for } x_2 = x_d'' \text{ as for turbine generators and machines with damper windings.} \quad (3)$$

$$T_3 = \frac{6e_0^2}{(x_2 + x_d'')^2}\left[r + 2r_2 - r_1\right]$$

Line-to-neutral short circuit may be calculated by adding $\left(\frac{x_0}{2}\right)$ to $x_d''$ and $x_2$ in the above formula and adding $r_0/4$ to the external resistance ($r$); except where $r_0$ is greater than $x_d''$.

The mechanical torque equation for two mechanically coupled rotors, obtained from equation (**17**) by putting all the decrement factors equal to zero, is:

$$T = \frac{I_1}{I_1 + I_2}\left\{\frac{T_1}{\left(\frac{\omega}{\omega_c}\right)^2 - 1}\sin \omega t - \frac{T_2}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\sin 2\omega t\right.$$

$$+ T_3\left[1 - \frac{4/3}{\left(\frac{\omega}{\omega_c}\right)^2 - 1}\cos \omega t + \frac{1/3}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\cos 2\omega t\right]$$

$$+ \frac{\omega}{\omega_c}\left[\frac{T_1}{\left(\frac{\omega}{\omega_c}\right)^2 - 1} - \frac{2T_2}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\right]\sin \omega_c t$$

$$\left. - T_3\left[1 - \frac{4/3}{\left(\frac{\omega}{\omega_c}\right)^2 - 1} + \frac{1/3}{\left(\frac{2\omega}{\omega_c}\right)^2 - 1}\right]\cos \omega_c t\right\} \quad (4)$$

*Notation.* Per unit notation is used for torques, currents, voltages, reactances and resistances; that is, the values are expressed as the number of times the unit value. The unit value for the several quantities is taken as follows:

Unit torque is the torque corresponding to rated speed with a kilowatt load equal to the kilovoltampere rating. For single-phase machines the reactances and resistances are based on the equivalent three-phase kilovoltampere, hence unit torque corresponds to a kilowatt load equal to $\sqrt{3}$ times the single-phase kilovoltampere.

Unit voltage is rated maximum phase voltage.

Unit current is rated maximum phase current.

Unit reactance (is what is usually termed 100 per cent reactance on the machine kilovoltampere base); in ohms per phase it is unit voltage divided by unit current. For single-phase machines unit reactance is based on the equivalent three-phase rating = $\sqrt{3}$ times the single-phase kilovoltampere.

*Unit resistance* is on the same basis as unit reactance and is identical numerically.

*List of Symbols.* The following list of symbols covers all the terms used more than once; a few others are defined as used.

$c$ = mechanical damping factor = $\frac{2I_2 n}{k}$.
$e_0$ = per unit voltage previous to short circuit.
$I_1$ = inertia of the coupled prime mover or other rotor (in. lb per sec$^2$).
$I_2$ = inertia of the rotor of the short-circuited machine.
$k$ = elastic constant of shaft, or springs (in. lb per radian).
$\eta$ = mechanical decrement factor for shaft or springs.
$r$ = per unit external resistance (positive or negative sequence).
$r_1$ = positive phase sequence resistance of the machine.
$r_0$ = zero phase sequence resistance of machine and external circuit.
$r_2$ = negative phase sequence resistance of the machine; for turbine generators $r_2$ should be corrected for saturation at the high current values.
$T$ = the (per unit) instantaneous mechanical torque.
$T_A$ = alternating component of the electrical torque.
$T_a$ = the armature time constant.
$T_{do}'$ = the transient open-circuit time constant.
$T_{do}''$ = the subtransient open-circuit time constant.
$T_{el}$ = the instantaneous electrical torque.
$T_L$ = loss component of the electrical torque.
$T_1$ = the initial amplitude of the rated frequency component, of electrical torque.
$T_2$ = the initial amplitude of the double frequency component.
$T_3$ = the initial value of the asymmetrical (*i.e.*, average) component of the loss torque.
$x_d$ = direct-axis synchronous reactance.
$x_d'$ = direct-axis transient reactance.
$x_d''$ = direct-axis subtransient reactance.
$x_q''$ = the quadrature-axis subtransient reactance.
$x_2$ = $\sqrt{x_d'' \cdot x_q''}$ the effective negative phase sequence reactance for single-phase short circuit.
$x_0$ = zero phase sequence reactance.
$\alpha$ = effective decrement factor for the initial decay of the rated frequency component of torque.
$\beta$ = effective decrement factor for the initial decay of the double frequency component of torque.
$\gamma$ = the effective decrement factor for the initial decrement of the loss component of torque.
$\epsilon$ = base of natural logarithms = 2.71.
$\phi$ = angle between the direct-axis and the axis of the short-circuited phase.

$\phi_1$ = per unit angle defining the position of the coupled rotor in space, unit angle being taken as the angular deflection of the shaft or the springs for unit torque.

$\phi_2$ = per unit angle defining the position of the rotor of the machine short-circuited.

$\omega$ = $2\pi f$, where $f$ is the rated frequency.

$\omega_c$ = $2\pi f_c$, where $f_c$ is the natural frequency of torsional oscillation.

## ELECTRICAL SHORT-CIRCUIT TORQUE

*Alternating Component.* Formulas for calculating the alternating component of short-circuit torque have been given by Penney[7] and others, but a recent paper[1] by Nickle, Pierce and Henderson gives a solution written in a series form equation (**5**), which is most usable. Penney's[7] torque formula was based on the change of stored magnetic energy. The authors of the former paper[1] start with a fundamental equation derived by Park[6] from considerations of the instantaneous power output for no change in stored magnetic energy. This same fundamental relation was derived from a still different point of view based on the fundamental distribution of flux and current in the air gap. The chief merit of the new derivation is that it gives a simple physical conception and makes possible the calculation of the radial forces in the air gap as well; however, space limitations do not permit including it here.

The equation for the alternating component of single-phase short-circuit torque $T_A$ is quoted from the paper[1] mentioned above, except for using $(\omega t)$ instead of $t$ and $\phi$ for $\alpha$.

$$T_A = \frac{e_0^2}{x_2 + x_d''} \left\{ 2FA \sum_{n=1,3,5\ldots} nb^{\frac{n-1}{2}} \sin n\,(\omega t + \phi) - \left[F^2 \frac{x_2}{x_2 + x_d''} + A^2 \frac{x_2 - x_d''}{x_2}\right] \sum_{n=2,4,6,\ldots} nb^{\frac{n-2}{2}} \sin n(\omega t + \phi) \right\} \tag{5}$$

where $F$ is the rotor interlinkage as a fraction of the initial value and $A$ is the armature interlinkage as a fraction of the maximum possible value at the instant of short circuit.

$$A = \epsilon^{-\frac{t}{T_a}} \cos\phi$$

$$F = \frac{x_d'' + x_2}{x_d + x_2} + \frac{(x_d'' + x_2)(x_d - x_d')}{(x_d + x_2)(x_d' + x_2)}\,\epsilon^{-\frac{t}{T_{d0}'}\left(\frac{x_d + x_2}{x_d' + x_2}\right)} + \frac{x_d' - x_d''}{x_d' + x_2}\,\epsilon^{-\frac{t}{T_{d0}''}\left(\frac{x_d' - x_2}{x_d'' + x_2}\right)} \;;\; b = \frac{x_2 - x_d''}{x_2 + x_d''}$$

*Loss Torques.* The component of torque due to the losses can be calculated from resistance losses produced by the instantaneous currents in the armature and the induced currents in the direct and quadrature axis rotor circuits. An accurate expression for the instantaneous loss in all the circuits at any time would necessarily be very complicated; however, a relatively simple expression may be obtained which is sufficiently accurate in the first few cycles where the loss torques are of consequence. To obtain this simple solution the effective rotor resistance in each axis will be taken as $2\,(r_2 - r_1)$; the factor 2 enters in this expression because $(r_2 - r_1)$ is only half the rotor loss for unit negative phase sequence current, since the other half is supplied mechanically by the rotor. This assumes that all of the components of armature current induce corresponding damper winding circuits, which is true only initially since after a few cycles the asymmetrical component of the damper current has disappeared completely.

For a line-to-line short circuit the loss in the armature circuit can be calculated also in terms of the direct and quadrature-axis components of current $(i_d)$ and $(i_q)$. The resistance coefficient for the armature circuit is $(r_1 + r)$ where $r$ is the external resistance per phase and $r_1$ the positive sequence resistance of the machine. It is true that the resistance coefficient for the asymmetrical current is something less than $r_1$, but the difference will have a negligible effect on the loss. The total resistance coefficient is then: $(r + 2r_2 - r_1)$, and the loss torque $(T_L)$ is:

$$T_L = [i_d^2 + i_q^2]\,(r + 2r_2 - r_1) \tag{6}$$

Neglecting the higher harmonics the components of current on a line-to-line short circuit are:

$$i_d = \frac{2e_0}{x_2 + x_d''}\,[F\cos(\omega t + \phi) - A]\cos(\omega t + \phi) \tag{7}$$

$$i_q = -\frac{2e_0}{x_2 + x_d''}\,[F\cos(\omega t + \phi) - A]\sin(\omega t + \phi) \tag{8}$$

Hence:

$$T_L = \frac{4e_0^2}{(x_2 + x_d'')^2}\left[\left(\frac{F^2}{2} + A^2\right) - 2FA\cos(\omega t + \phi) + \frac{F^2}{2}\cos 2\,(\omega t + \phi)\right][r + 2r_2 - r_1] \tag{9}$$

For a line-to-neutral short circuit $(x_0/2)$ should be added to both $x_d''$ and $x_2$, also $(1/2)(r_0)$ should be added to the external resistance $(r)$ to take into account the neutral resistance which may be quite high. Where the neutral resistance is of the same order as the reactance, its effect in limiting the current should also be taken into account.

*Approximations for the Initial Decrement.* The accurate expression for the electrical torque is given by the sum of equations (**5**) and (**9**); but for calculations of mechanical torques in the shafts of two coupled rotors, or in the springs of spring-mounted machines, it is desirable to simplify these expressions. Since, except for cases near resonance, the peak mechanical torque will occur within one cycle of the natural oscillation, approximations for $F$ and $A$, which are accurate for a few cycles, will be used. The other necessary assumptions are the same as stated for the simplified calculations.

For the first few cycles, the following approximations are made:

$$F \gtrsim \epsilon^{-\sigma_f t} \text{ and } A \approx \epsilon^{-\sigma_a t} \qquad (10)$$

where

$$\sigma_f = \frac{1}{T_{d0}''}\left(\frac{x_d' - x_d''}{x_d'' + x_2}\right) \text{ and } \sigma_a = \frac{1}{T_a} \qquad (11)$$

In simplifying equation (5), the decrement of the double frequency torque will be considered determined by $F^2$—the error being small, since the coefficient of $A^2$ is smaller than that of $F^2$. With these approximations:

$$T_{el} = T_1\,\epsilon^{-\alpha t}\sin\omega t - T_2\,\epsilon^{-\beta t}\sin 2\omega t$$
$$+ T_3\left[\epsilon^{-\gamma t} - 4/3\,\epsilon^{-\alpha t}\cos\omega t + 1/3\,\epsilon^{-\beta t}\cos 2\omega t\right] \qquad (12)$$

For single-phase short circuits, the values of $T_1$, $T_2$ and $T_3$ are as given by equation (3); and:

$$\left.\begin{aligned} \alpha &= \sigma_f + \sigma_a \\ \beta &= 2\sigma_f \\ \gamma &= 2/3\,(2\sigma_a + \sigma_f) \end{aligned}\right\} \qquad (13)$$

## MECHANICAL SHORT-CIRCUIT TORQUES

*Shaft Torques.* The mechanical torque in the shaft and coupling between two coupled rotors may be analyzed as follows. The equation of static equilibrium of the two rotors can be written:

$$\left.\begin{aligned} I_1\phi_1'' + k\,(\phi_1 - \phi_2) &= 0 \\ I_2\phi_2'' - k\,(\phi_1 - \phi_2) &= T_{el} \end{aligned}\right\} \qquad (14)$$

and introducing the shaft torque $T = k\,(\phi_2 - \phi_1)$, and mechanical damping, we have:

$$\left[\frac{I_2}{k}\right]T'' + c\,T' + \left[\frac{I_1 + I_2}{I_1}\right]T = T_{el} \qquad (15)$$

which we now write as:

$$\left(\frac{I_2}{k}\right)T'' + c\,T' + \left(\frac{I_1 + I_2}{I_1}\right)T$$
$$= T_1\epsilon^{-\alpha t}\sin\omega t - T_2\epsilon^{-\beta t}\sin 2\omega t$$
$$+ T_3\left[\epsilon^{-\gamma t} - 4/3\,\epsilon^{-\alpha t}\cos\omega t + 1/3\,\epsilon^{-\beta t}\cos 2\omega t\right] \qquad (16)$$

from equation (12), calling:

$$\eta = \frac{c\,k}{2I}$$

$$\omega_c^2 = \frac{k\,(I_1 + I_2)}{I_1 I_2}$$

and $\omega_c'^2 = \omega_c^2 - \eta^2$,

the *complete expression for the mechanical torque in the shaft* is:

$$T = \frac{T_1\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2\epsilon^{-\alpha t}}{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]^2 + [2\,(\alpha - \eta)\,\omega]^2}$$
$$\{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]\sin\omega t + [2\,(\alpha - \eta)\,\omega]\cos\omega t\}$$

$$- \frac{T_2\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2\cdot\epsilon^{-\beta t}}{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]^2 + [4(\beta - \eta)\,\omega]^2}$$
$$\{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]\sin 2\omega t + [4(\beta - \eta)\,\omega]\cos 2\omega t\}$$

$$+ T_3\left(\frac{I_1}{I_1 + I_2}\right)\omega_c^2\left[\frac{\epsilon^{-\gamma t}}{[(\omega_c)^2 - 2\eta\gamma + \gamma^2]}\right.$$

$$- \frac{4/3\,\epsilon^{-\alpha t}}{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]^2 + [2\,(\alpha - \eta)\,\omega]^2}\cdot$$
$$\{[(\omega_c')^2 - \omega^2 + (\alpha - \eta)^2]\cos\omega t - [2\,(\alpha - \eta)\,\omega]\sin\omega t\}$$

$$+ \frac{1/3\,\epsilon^{-\beta t}}{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]^2 + [4\,(\beta - \eta)\,\omega]^2}\cdot$$

$$\left.\{[(\omega_c')^2 - (2\omega)^2 + (\beta - \eta)^2]\cos 2\omega t - [4(\beta - \eta)\,\omega]\sin 2\omega t\}\right]$$

$$+ \frac{I_1}{I_1 + I_2}\cdot\epsilon^{-\eta t}\,[T'\sin\omega_c' t + T''\cos\omega_c' t] \qquad (17)$$

The values of $T'$ and $T''$ are determined from the conditions at the time ($t = 0$) of the short circuit. These are $T = T' = 0$, for a short circuit from no load.

The fundamental concepts are brought out by neglecting the electrical and mechanical decrements. For the case of resonance, which is sometimes important, these decrements may not be neglected and play an important part. As indicative of the phenomena, consider the type case:

$$T'' + 2\eta T' + \omega_c^2 T = \frac{T_1 k}{I_2}\,\epsilon^{-\alpha}\cdot\sin\omega_c^1 t \qquad (18)$$

The solution of this equation with the arbitrary constants indicated follows directly from (17) and is

$$T = \frac{T_1\left(\dfrac{I_1}{I_1 + I_2}\right)\omega_c^2}{(\alpha - \eta)^2 + 4\,(\omega_c^1)^2}\left\{[\epsilon^{-\alpha t} + \epsilon^{-\eta t}]\sin\omega_c^1 t\right.$$
$$\left. + \frac{2\omega_c^1}{(\alpha - \eta)}[\epsilon^{-\alpha t} - \epsilon^{-\eta t}]\cos\omega_c^1 t\right\} \qquad (19)$$

The interesting part to observe here is that $\alpha$ and $\eta$ enter the equations practically identically, *i.e.*, the resultant action under an exponentially decaying sinusoidal force is not unlike that of a pure sinusoidal force with mechanical damping.

*Spring-Mounted Stators.* For the case of the spring-mounted stator, a little examination shows that the above relations hold exactly, where $k$ is the rotational spring constant of the spring system, $I_1 = \infty$ (the foundation) and $I_2$ = rotational inertia of stator.

*Experimental Determination of Short-Circuit Torque and Example.* The special construction of the spring-mounted stator has made it particularly adaptable for the experimental determination of short-circuit torques. Earlier experimentors[9,10] have resorted to measurements on the rotor proper and while they have been exact, there are definite limitations not existent in the type of test discussed here. The method suggests itself of measuring the frame foot reaction, using a piezo-electric measuring device,[5] but the disadvantage here would be in making the assumption that the frame was inflexible.

The tests discussed here were carried out by Mr. E. A. Tulus,* who also designed the accelerometer used to check stator inertia torques. Spring torques were determined directly by recording the instantaneous deflections of the spring groups by means of the direct reading Geiger vibrograph. For the purpose of test, a large single-phase 60-cycle generator was employed, but tested at 25 cycles to bring out the importance of torque oscillations at the natural period. Now from equation (**14**),

$$I\phi'' + k\phi = T_{el}$$

or

$$T_{inertia} + T_{spring} = T_{electrical}$$

so that by measuring both $T_{sp}$ (by the vibrograph) and $T_i$ (by the accelerometer), the instantaneous values of $T_{el}$ were checked. However, since the prime interest in our test was $T_{sp}$, Fig. 1 shows the values as measured and as calculated from equation (**17**). The machine constants were:

$x_2 = x_d'' = 0.18$ $e_0 = 1$ $I = 7.7\text{x}10^6$ in. lb sec$^2$
$x_d' = 0.30$ $2r_2 - r_1 = 0.014$ $k = 6.0\text{x}10^{10}$ in. lb per radian
$x_d = 1.20$ $r = 0$ $\alpha = 19.5$
$T_{d0}' = 6.5$ sec $T_1 = 5.6$ $\beta = 14.0$
$T_{d0}'' = 0.05$ sec $T_2 = 2.8$ $\gamma = 21.0$
$T_a = 0.08$ sec $T_3 = 0.6$ $\eta = 5.0$

It is important to realize that the major contributing torque oscillations are those at the natural period of oscillation of the machine. The test shown was for a single-phase line-to-line short circuit, near the instant of zero voltage. The coincidence between test and calculation is striking. The expression for the spring torque, figures out to be:

$$\begin{aligned} T = {} & \epsilon^{-19.5t}\,[-\,2.21 \sin \omega t + 1.03 \cos \omega t] \\ & + \epsilon^{-14t}\,[0.23 \sin 2\omega t] + \epsilon^{-21t}\,[0.75] \\ & + \epsilon^{-5.t}\,[3.45\ \omega_c' t - 1.78 \cos \omega_c' t] \end{aligned} \qquad (\mathbf{20})$$

For $\alpha = \beta = \gamma = \eta = 0$, the expression is,

$$\begin{aligned} T = {} & [-\,2.55 \sin \omega t + 0.36 \cos \omega t + 0.25 \sin 2\omega t \\ & + 0.60 + 3.68 \sin \omega_c t - 0.96 \cos \omega_c t] \end{aligned} \qquad (\mathbf{21})$$

The difference in the peak torque, in the first cycle, is of the order of 20 per cent,—the simpler calculation being on the safe side.

*Short-Circuit Stresses in Stators.* The question of mechanical reactions in the stator revolves around the foundation bolt, frame foot, and frame section stresses. Due to the relative stator rigidity, the electrical torques are considered to act undiminished. This is no handicap to stator design, since even short-circuit torques result in low stresses. Considering the torque as uniformly distributed around the stator bore, and referring to Fig. 2, the distribution of forces as shown in c determines essentially the stresses in the stator. We thus have a statically indeterminate structure to solve, when the normal force and bending momentat point $O$ at the top of the stator are zero. Following ideas usually resorted to in such cases,[8] from conditions of symmetry the point $O$ does not move during short circuit. This fact is given by $\dfrac{\partial u}{\partial s} = 0$, where $u$ is the stored energy in the strained stator half. This condition expanded is

$$\int_0^{\phi_a} M_1 \sin \phi d\phi + \int_{\phi_a}^{\pi} M_2 \sin \phi d\phi = 0 \qquad (\mathbf{22})$$

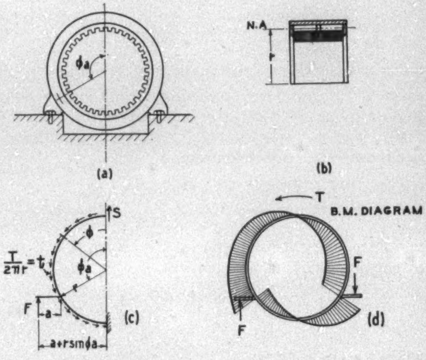

FIG. 2—SHORT-CIRCUIT STRESSES IN STATORS

where

$$M_1 = Sr \sin \phi + tr^2 (\phi - \sin \phi);\ 0 < \phi < \phi_a \qquad (\mathbf{23})$$

$$\begin{aligned} M_2 = {} & Sr \sin \phi + tr^2 (\phi - \sin \phi) \\ & - Fr (\sin \phi_a - \sin \phi) - Fa;\ \phi_a < \phi < \pi \end{aligned} \qquad (\mathbf{24})$$

$r$ = radius to the neutral axis
$E$ = modulus of elasticity
$\Gamma$ = moment of inertia of frame section

Solution of (**22**) gives the expression for $S$ which substituted in (**23**) and (**24**) evaluates the bending moments:

$$S = \frac{T}{2\pi r}\left[1 + \frac{\cos \phi_a \left(2\dfrac{a}{r} + \sin \phi_a\right) - (\pi - \phi_a)}{a/r + \sin \phi_a}\right] \qquad (\mathbf{25})$$

$$M_1 = \frac{T}{\pi}\left[\phi + \left(\cos \phi_a - \frac{\pi - \phi_a}{a/r + \sin \phi_a}\right) \sin \phi\right] \qquad (\mathbf{26})$$

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*Westinghouse Elec. & Mfg. Co., Railway Engg Dept.

$$M_2 = \frac{T}{\pi}\left[\phi - \pi + \left(\cos\phi_a + \frac{\phi_a}{a/r + \sin\phi_a}\right)\sin\phi\right] \quad (27)$$

The difference between $M_1$ and $M_2$ at $\phi = \phi_a$ is the concentrated bending moment, $Fa$. The distribution is shown typically in Fig. 2d. The maximum value of $M$ usually is at $\phi = \phi_a$, but not always. For the case of a 43,500-kva, 1,800-rpm turbine generator the constants are:

$T = 2 \times 10^7$ in.-lb $\quad a \simeq 0$
$r = 95$ in. $\quad I = 3{,}420$ in.$^4$
$\phi_a = 120$ deg. $\quad Z = \dfrac{I}{c} = 1{,}000$ in.$^3$

Thus the bending moment at $\phi = \phi_a$ is $M_{max} = 0.1T$, *i.e.*, the maximum bending moment is about 10 per cent of the short-circuit torque for this case. Very often, however, it reaches 40 per cent of $T$. The corresponding stress is

$$S = \frac{0.1 \times 2 \times 10^7}{1{,}000} = 2{,}000 \text{ lb per in.}^2$$

which is very low.

## OTHER TRANSIENT TORQUES

*Running Out of Synchronism.* The electrical torque ($T_s$) produced under this condition can be approximated as,

$$T_s = \frac{E_{d1} \cdot E_2}{x_d + x} \sin s\,\omega t \quad (28)$$

where $E_{d1}$ is the voltage back of synchronous reactance for the machine considered, $x$ is the reactance of the system to which it is connected and $E_2$ is the voltage back of this reactance, and $s$ is the per unit slip.

The general method of calculating the effect of passing through resonance at a constant amplitude of applied force has been worked out by F. M. Lewis,[3] and experimental results given by J. G. Baker and E. A. Tulus.[3] The curves of Fig. 3 give resulting torque in number of times the applied torque for different rates of passing through. The applied torque ($T_0$) is in this case $(I_1T_s)/(I_1 + I_2)$. These curves may be used providing the rate of passing through is not changing too rapidly. The average rate of change in speed may be calculated from the stored energy and the induction motor torque.

Under certain conditions a machine actually may reach a stable condition and run at a definite slip, such a case is described in an article[2] by A. A. Kroneberg. If this stable slip frequency should be close to the natural frequency, the resulting torque would reach serious magnitudes.

*Synchronizing Out of Phase.* If a machine is running at synchronous speed with the voltage equal numerically to the line voltage ($E_t$), but out of phase by an angle ($\delta$) at the instant of connecting to the line, the alternating electrical torque for the first few cycles is equivalent to that of a sudden short circuit at a voltage $e_0 = E_t\sqrt{2 - 2\cos(\delta)}$. For a polyphase machine the transient is similar to a polyphase short circuit at this voltage. Space does not permit including this formula, but the alternating torque can be approximated by taking the fundamental frequency only in the single-phase torque expression.

The suddenly created average torque ($T_\delta$) due to the power surge tending to pull the machines into step, can be approximated in the first few cycles by

$$T_\delta = \frac{E_t^2}{x_d'' + x}\sin\delta \quad (29)$$

The mechanical torque in the shaft resulting from this component is:

$$T = \frac{E_t^2}{(x_d'' + x)}\sin\delta\left(\frac{I_1}{I_1 + I_2}\right)[1 - \cos\omega_c t] \quad (30)$$

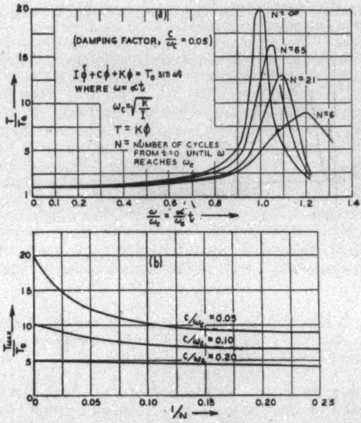

FIG. 3—CURVES SHOWING VIBRATION AMPLITUDES ON GOING THROUGH RESONANCE

The peak value indicated by this formula will be reduced by the electrical decrement about the same degree as for sudden short circuit.

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## Discussion

**R. Baudry:** Since this paper was written, the writer has calculated (in collaboration with the authors of the paper) the mechanical torques in the shafts of a tandem compound turbine generator, where the rotating element is composed of 3 masses connected by 2 shafts. In this case, the problem becomes more complicated; the mechanical and electrical decrements can be neglected in order to simplify the solution. The mechanical torques thus calculated are slightly larger, and so the calculation is on the safe side.

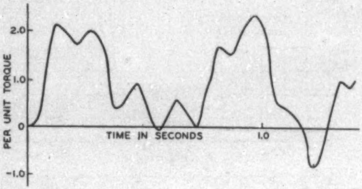

FIG. 1—GENERATOR SHAFT TORQUE FOR SINGLE-PHASE SHORT CIRCUIT ON A TANDEM COMPOUND TURBINE GENERATOR UNIT

In this case, there are 2 critical speeds, $\omega_1$ and $\omega_2$. Using the same notation as in the paper, the 2 critical speeds are obtained from the following bi-quadratic equations:

$$\omega^4 + \left[ K_1\left( \frac{1}{I_1} + \frac{1}{I_2} \right) + K_2\left( \frac{1}{I_2} + \frac{1}{I_3} \right) \right] \omega^2 + K_1K_2\left( \frac{1}{I_1I_2} + \frac{1}{I_1I_3} + \frac{1}{I_2I_3} \right) = 0$$

The applied electrical torque can be written in the following form:

$$T_{el} = T_k + T_{sn} \sin n\omega t + T_{cn} \cos n\omega t$$

The mechanical torques in the shaft are:

$T_1$ between the generator and the high pressure turbine.

$T_2$ between the high pressure and low pressure turbines.

These torques are obtained from the two following equations:

$$T_1'' + K_1\left( \frac{1}{I_1} + \frac{1}{I_2} \right) T_1 - \frac{K_1}{I_2} T_2 = T_{el} \times \frac{K_1}{I_1}$$

$$T_2'' + K_2\left( \frac{1}{I_2} + \frac{1}{I_3} \right) T_2 - \frac{K_2}{I_2} T_1 = 0$$

Following is given the mechanical torque $T_1$ produced in the shaft by $T_{el}$.

$$T_1 = T_k \left\{ \frac{\dfrac{K_1}{I_1} - \dfrac{I_2 + I_3}{I_1 + I_2 + I_3}\,\omega_2^2}{\omega_2^2 - \omega_1^2} \cos \omega_1 t + \frac{\left( \dfrac{I_2 + I_3}{I_1 + I_2 + I_3} - \dfrac{K_1}{I_1} \right)}{\omega_2^2 - \omega_1^2} \cos \omega_2 t + \frac{I_2 + I_3}{I_1 + I_2 + I_3} \right\}$$

$$+ T_{sn} \frac{K_1}{I_1} \left\{ \frac{n\omega}{\omega_1} \; \frac{K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right) - \omega_1^2}{(\omega_2^2 - \omega_1^2)\,(n^2\omega^2 - \omega_1^2)} \sin \omega_1 t + \frac{n\,\omega}{\omega_2} \; \frac{\omega_2^2 - K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right)}{(\omega_2^2 - \omega_1^2)\,(n^2\omega^2 - \omega_2^2)} \sin \omega_2 t + \frac{K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right) - n^2\omega^2}{(n^2\omega^2 - \omega_1^2)\,(n^2\omega^2 - \omega_2^2)} \sin n\omega t \right\}$$

$$+ T_{cn} \frac{K_1}{I_1} \left\{ \frac{K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right) - \omega_1^2}{(\omega_2^2 - \omega_1^2)\,(n^2\omega^2 - \omega_1^2)} \cdot \cos \omega_1 t + \frac{\omega_2^2 - K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right)}{(\omega_2^2 - \omega_1^2)\,(n\omega^2 - \omega_2^2)} \cdot \cos \omega_2 t + \frac{K_2\left( \dfrac{1}{I_2} + \dfrac{1}{I_3} \right) - n^2\omega^2}{(n^2\omega^2 - \omega_1^2)\,(n^2\omega^2 - \omega_2^2)} \cos n\omega t \right\}$$

The curve in Fig. 1 gives the mechanical torque $T_1$ produced in the shaft of a tandem compound turbine generator set.

**J. F. Calvert:** Considerable material has been published heretofore on the large alternating torques of electromagnetic origin, which are present following short circuits. These are of importance in the stator. The discussion in this paper of the electrical loss torques probably is the first serious study of this problem which has been published. These loss torques are shown to be of at least equal importance with the alternating ones so far as the rotor couplings are concerned. The studies given to torques due to synchronizing out-of-phase, and to those due to pulling-out-of-step, also are new and equally valuable contributions.

The authors have allowed very little space to the derivation of formulas for electrical torques. It may be of some interest to add a short discussion of this feature which will give something of a physical picture of the problem.

In an article on *Forces in Turbine Generator Stator Windings* (TRANSACTIONS A.I.E.E., March, 1931, p. 178), the writer gave a physical interpretation of the calculation of electromagnetic forces from $\int H^2 \cdot ds$, over some surface in air which encircles a conductor carrying current. The methods shown in Appendix D of that article are directly applicable to the problems of torques or tangential forces acting on solid parts adjacent to the air gap, and also to radial forces acting on these solid parts.

If the stator bore were assumed to be a smooth iron surface carrying thin current sheets, it would be found that when torques were exerted on this member, the flux would enter at an oblique angle. This surface may be considered as a series of very small angular saw-toothed pieces. One side of each tooth lies exactly along a flux line and consists only of a current sheet, which receives the ampere turn surfaces. There is a force exerted on this current sheet tending to force it out of the air gap. The other side of each saw tooth coincides with an ampere turn surface, and consists only of iron, which receives the flux lines. There is a force exerted on the latter surface tending to pull it into the air gap. The magnitude of these forces is $\dfrac{0.0139}{10^6} B_R^2$ lb per square inch, where $B$ is given in lines per square inch.

From Fig. 2, the tangential force per unit of actual stator surface area is

$$F_t = \frac{0.0139}{10^6} (2\, B_R^2 \cos\theta \sin\theta)$$

$$= \frac{0.0139}{10^6} (2\, B_t \cdot B_R)$$

$B_t$ = tangential component of $B_R$
$B_r$ = radial component of $B_R$

Similarly, the outward radial or bursting force in pounds per square inch is

$$F_r = \frac{0.0139}{10^6} (B_R^2 \sin^2\theta - B_R^2 \cos^2\theta)$$

$$= \frac{0.0139}{10^6} (B_t^2 - B_r^2)$$

This bursting force can be extremely large when taken over the total area of the stator bore. It appears during certain instants after short circuit when the tangential densities exceed the radial densities over a large part of the air gap. It is a factor to be considered in low reactance split frame machines.

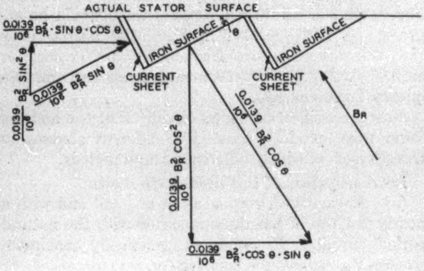

FIG. 2

Returning to the tangential component to derive an expression for torque

$$T = \frac{A}{\pi} 2 \int_0^{\pi} [B_{rd} \cos(s) + B_{rq} \sin(s)][B_{td} \cos(s) + B_{tq} \sin(s)]\,ds$$

or

$$T = A\,(B_{rd}B_{td} + B_{rq}B_{tq})$$

when

$B_{rd}$ = maximum radial value of direct axis component
$B_{rq}$ = maximum radial value of direct axis component
$B_{td}$ = maximum tangential value of direct axis component
$B_{tq}$ = maximum tangential value of direct axis component
$A$ = total stator bore surface in square inches

This can be used as a basis for calculating torques. The densities can then be put in any more convenient terms as desired, such as voltage, current, and reactance, etc.

**I. A. Terry:** The authors have presented a very careful and interesting analysis of the transient torques in synchronous machines and have shown clearly the influence of the various factors, which enter the problem, upon the final result. The method of introducing resistance losses into the equations represents a very satisfactory engineering method of handling a problem that is of great mathematical complexity. The value of $T_3$ given in equations (3) indicates that it cannot be neglected entirely as has been done by previous authors.

The practical application of the analysis concerns manufacturing companies as well as construction and operating companies. It is necessary to design rotating machinery so that the stresses set up during electrical disturbances will not produce permanent deformation of parts. Furthermore, it is necessary to have the foundation design ample to withstand the forces to which it is subjected. Since the cost of the foundation is an item of considerable magnitude in any installation, it is not possible to make an economical design without a fairly accurate knowledge of the forces involved under all conditions of operation which may occur.

The electrical torque produced under conditions of operating out of synchronism and the possibility of passing through a resonance point at some value of slip shows very clearly the advisability of providing protective devices to remove the machine from the electrical supply before the slip approaches the critical value.

**L. A. Kilgore:** Mr. J. F. Calvert's discussion develops a formula for torque in terms of the fundamental components of the flux in the air gap. Using per unit notation, Mr. Calvert's final equation can be written:

$$T = B_{rd}B_{td} + B_{rq}B_{tq}$$

This can be expressed in terms of the direct and quadrature axis components of armature current ($id$) and ($iq$), and the components of per unit excitation ($I_{de}$) and ($I_{qe}$): (using the reactances as defined and $Xe$ = armature leakage reactance).

$$B_{rd} = I_{de} - id\,(X_d - X_l)$$
$$B_{rq} = I_{qe} - iq\,(X_q - X_l)$$
$$B_{td} = -\,iq$$
$$B_{tq} = -\,id$$

Hence,

$$T = iq\,I_{de} - id\,I_{qe} - id\,iq\,(X_d - X_q)$$

which is the equation from which equation (5) of the paper was derived. Park (reference 6 in bibliography) derives this same equation from consideration of the instantaneous power output with no change in stored magnetic energy.

Another interesting variation of this fundamental relation may be obtained in terms of the per unit voltage back of sub-transient reactance on the two axes ($E_d''$) and ($E_q''$):

$$B_{rd} = E_{td} + idX_e = E_d'' - id\,(X_d'' - X_l)$$
$$B_{rq} = E_{tq} + iqX_e = E_q'' - iq\,(X_q'' - X_l)$$
$$T = i_q\,E_d'' - id\,E_q'' - id\,iq\,(X_d'' - X_q'')$$

# The Effect of Transient Voltage Protective Devices on Stresses in Power Transformers*

BY K. K. PALUEFF† and J. H. HAGENGUTH†
Member, A.I.E.E. Associate, A.I.E.E.

It is well known that extreme high voltage stresses are developed in transformer windings when transient voltages are applied to the transformer terminals. These stresses can be reduced by internal means—electrostatic shielding as is done in non-resonating transformers and was discussed in previous papers;[1,2,3,4] or by external means—changing the shape or the amplitude of the applied wave or both. The shape of the applied wave can be controlled by "wave modifiers," while lightning arresters and gaps control primarily the amplitude of the applied wave. The effectiveness of these devices is discussed in the present paper.

Once a traveling wave of any shape is formed on a transmission line, its future behavior at all points of the system can be calculated with engineering accuracy. Since theoretical and experimental studies have proved the effectiveness of ground wires in shielding of lines and stations from direct lightning strokes, only traveling waves are considered in this paper.

## Part I

### EFFECT OF TERMINAL WAVE SHAPE ON INTERNAL STRESSES

Stresses produced in windings of power and distribution transformers by operating frequency voltage are directly proportional to the amplitude of the applied voltage and the turn ratio factors. Stresses produced by short time transients are independent of the turn ratio, and depend on the amplitude and shape of the applied wave and whether it is a single impulse (lightning wave) or a train of waves (switching surge). Unless the transformer winding has been made non-resonating by means of proper electrostatic shielding, it will undergo violent oscillations when a single wave of vertical front and of relatively long duration is applied. This oscillation is composed of some 11 space harmonics, each oscillating at its own frequency.

The transient voltage between any 2 points in a transformer is the algebraic sum of all the harmonic voltages. However, the 1st to 4th harmonics are chiefly responsible for the voltage to ground, the 4th to 7th harmonics for the voltage between adjacent coils and the 7th to 11th harmonics for the voltage between adjacent turns. At the moment of impact of a sheer front wave, all harmonics are in phase at the line end of the winding, and elsewhere they are either in phase or in phase opposition. Hence, coil and turn stresses are highest at the line end.

There is a definite relation between the front and length of an applied impulse wave, and the resulting amplitudes of these harmonics. The reaction of a given transformer to a given wave can be determined with engineering accuracy when the *ratio* of the duration of the front and the tail of a wave to the period $T$ of the fundamental (slowest) harmonic is known. It is useful therefore to express a wave in terms of this period which is referred to as the natural period of the transformer. For instance a 1.5/40 microsecond wave would be expressed as $0.0075/0.20\ T$ if $T = 200$ microseconds (*i.e.*, transformer natural frequency = 5,000 cycles) or as $0.03/0.80\ T$ if $T = 50$ microseconds (natural frequency 20,000 cycles).

Such a classification shows directly that one and the same wave produce essentially different stresses in transformers of widely different natural periods.

Previous papers of this series have shown:

(a) A wave with vertical front and tail and with a nearly flat top of length comparable with the natural period ($0/1.0/0\ T$) produces practically maximum stresses throughout the transformer.

(b) A wave like (a) but with about half the length ($0/0.50/0\ T$) produces the same coil and turn insulation stresses as (a) but may result in considerably higher major insulation stresses near the neutral end.

(c) A wave like (a) but with much shorter length produces the same major insulation stresses at the line end as (a) or (b), but much lower stresses elsewhere, and in some cases much higher coil and turn stresses.

(d) A wave with vertical front and with an exponential tail comparable in length with the natural period ($0/1.0\ T$ wave) produces maximum stresses between coils and turns and almost maximum stresses in the entire major insulation.

(e) With increasing length of a sheer front wave, the internal voltages to ground increase, approaching a maximum as shown in Fig. 1, curve 1.

All harmonics with natural periods shorter than the front of the applied wave are practically eliminated. Sloping the wave front, therefore, reduces the voltage stresses between turns, coils, and in the major insulation. However, the stresses on the major insulation *at the line end* can not be reduced by a change in the shape of the wave of a given amplitude. The stresses produced in the major insulation by a sheer front wave can, *except at the line end*, be reduced by making the wave much shorter than half the natural period $T$.

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*This is the fifth of a series of papers under the general title, *The Effect of Transient Voltages on Power Transformer Design.*

†Power Trans. Engg Dept., General Electric Co., Pittsfield, Mass.

1. For references see bibliography.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

The possible reduction of stresses by slanting of front and tail of a wave is given in the table below. Stresses produced by a wave with front and tail sufficiently slanted to produce uniform voltage distribution are compared with those produced by a wave with sheer front and long tail, both waves having the same amplitude.

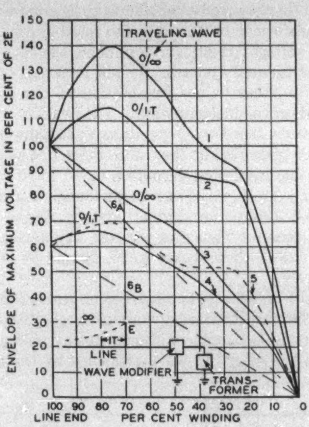

FIG. 1—COMPARISON OF MAXIMUM VOLTAGES PRODUCED BY WAVES OF DIFFERENT LENGTH IN A TRANSFORMER. (100% IS THE AMPLITUDE OF VOLTAGE PERMITTED BY STANDARD COORDINATION GAP)

1, 2 transformer not protected
3, 4 transformer protected by wave modifier
5 transformer protected by thyrite lightning arrester
6 ideal non-resonating transformer
*A* without protection
*B* protected by standard thyrite lightning arrester

The wave modifier is designed to slope the front of a very long traveling wave to $1.2T$ microseconds

TABLE I

| | Relative stresses in grounded neutral transformer | | Relative stresses in isolated neutral transformer | |
|---|---|---|---|---|
| At line end | Sheer front wave | Long front wave | Sheer wave | Long front wave |
| Turn insulation | 1 | 0.01 to 0.003 | 1 | 0.01 to 0.003 |
| Coil insulation | 1 | 0.05 to 0.030 | 1 | 0.05 to 0.030 |
| Major insulation | 1 | 1 | 1 | 1 |
| At other points | | | | |
| Turn insulation | 1 | 0.07 to 0.030 | 1 | 0.07 to 0.03 |
| Coil insulation | 1 | 0.30 to 0.15 | 1 | 0.30 to 0.15 |
| Major insulation | 1 | 0.80 to 0.20 | 1 | 0.80 to 0.50 |

To reduce turn, coil and major insulation stresses to values of the same order of magnitude as would exist if the voltage distribution along the winding were essentially uniform, the minimum length $t_2$ of the front of the terminal wave of a given amplitude must be approximately as follows:

For the reduction of turn stresses

$$t_2 = 0.10\,T \text{ to } 0.20\,T$$

For the reduction of turn and coil stresses (Fig. 2)

$$t_2 = 0.40\,T$$

For the reduction of turn, coil and major insulation stresses (Fig. 1)

$$t_2 = 1.20\,T$$

## EFFECT OF AMPLITUDE

The distributed constants of a transformer do not change appreciably with amplitude of the voltage, and therefore the stresses produced by a wave of a given shape are directly proportional to its amplitude.

The time lag of air gaps or station insulation allows steep waves to reach higher maximum amplitudes than indicated by their 60-cycle arcover. This effect, combined with those mentioned above, causes short waves to produce much higher stresses than do long waves. However, the shorter waves may or may not cause greater stresses in the major insulation of the rest of the winding, since the effects of an increase in maximum possible amplitude permitted by time lag and shorter length of wave partially offset each other in this case. Hence, every transformer has its own critical wave length which produces the maximum stresses in major insulation, and this wave length depends upon the *time lag characteristics* of the voltage limiting devices and the natural period $T$ of the transformer.

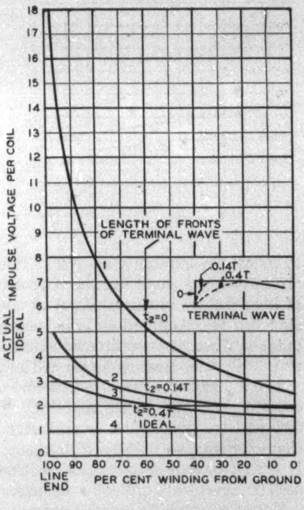

FIG. 2—REDUCTION OF COIL STRESSES DUE TO LENGTHENING OF THE FRONT OF THE TERMINAL WAVE

## Part II

### EFFECTIVENESS OF PROTECTIVE DEVICES

Protective devices can be divided into 3 classes, which have markedly different effects on internal transformer stresses: (1) air gaps, (2) lightning arresters and (3) wave modifiers.

*1. Air Gaps, (Rod Gaps, Arcing Rings, Sphere Gaps, etc.)* These gaps are simple in construction, definite in action, and of low cost, but they permit power current to follow the impulse sparkover. Their disadvantages are in giving a small margin of protection under that of high voltage bushings, if set at levels suggested as standard for coordination; in increasing the number of outages, if set for lower arcover values; and in chopping wave tails, thus creating higher coil and turn stresses.

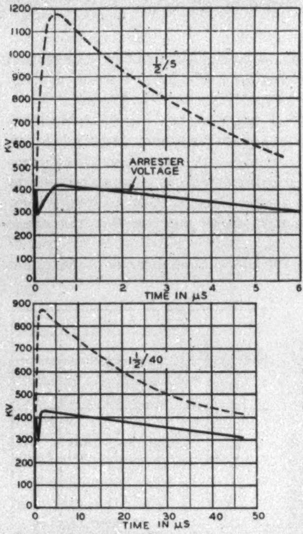

FIG. 3—MODIFICATION OF TRAVELING WAVES BY A THYRITE LIGHTNING ARRESTER

Dotted lines—terminal wave without arrester

Solid lines—Terminal wave with arrester

The rod gap is the most satisfactory of all air gaps for coordination, due to its simplicity, independence of dirt and wetting, and the similarity of its time lag characteristics with those of bushings and insulators. It should be looked upon as a last line of defense and used irrespective of protective devices.

However, the high impulse ratio of the rod gap and arcing rings for steep waves makes them inferior to a sphere gap, which has unity impulse ratio. As the arcover voltage of a wet sphere gap is only about 40 to 45 per cent of the dry value, housing the gap is necessary for the best protection. Several small sphere gaps in series may be used, in which case their total volume is inversely proportional to the square of their number.

*2. Lightning Arresters.* Fig. 3 shows 0.5/5 and 1.5/40 microsecond waves appearing across transformer terminals with and without protection by a standard thyrite lightning arrester. The arrester does not change the steepness of front or the duration of the tail of the wave, but only reduces the amplitude and the rate of fall of voltage, hence reducing the transformer stresses approximately in proportion to the amplitude. A properly installed thyrite arrester will limit the maximum voltage on a transformer to 3.5 times the rated system line to ground voltage (crest) for grounded systems, or 4.3 times for isolated systems. It will limit the transient voltage to these values irrespective of the shape or amplitude of the incident wave. The relative reduction in amplitude, therefore, depends on the maximum wave amplitude permitted by the transmission line insulation. Normal line insulation permits a 0.5/5 wave to reach 9.5 times, a 1.5/40 wave 7 times, and much longer waves about 5.8 times the normal system line-to-ground voltage (crest). Thus the arrester would reduce the stresses due to these waves to 37, 50 and 60 per cent, respectively.

A thyrite arrester gives much better protection than a rod gap, because its time lag is almost negligible, a much lower setting is possible without causing outages, and it avoids the sheer tail wave produced by the arcover of a rod gap, the rate of fall of the tail of the wave being even less than that of the incident wave. A rod gap due to its time lag will allow a 0.5/5 wave to reach an amplitude about 64 per cent higher than the arrester allows. Also, a rod gap set to arcover at the same voltage for 0.5/5 or 1.5/40 waves as the arrester would cause outages from many switching surges.

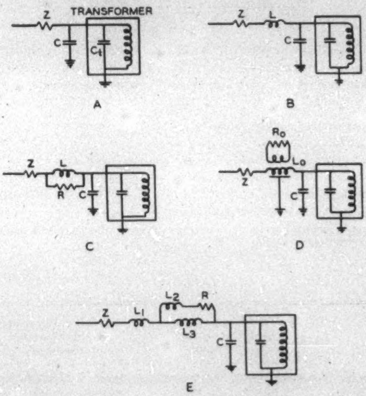

FIG. 4—WAVE MODIFIER CIRCUITS

*3. Wave Modifiers (Fig. 4).* As has been shown above, a very substantial reduction of internal stresses in transformer windings can theoretically be accomplished by a proper modification of the shape of the incoming traveling wave without changing its amplitude.

Sometimes wave modifiers are called wave absorbers. This is a misapplication of the term because all available protective devices absorb a negligible fraction of the energy of waves.

There are 5 degrees of protection that a wave modifier can be called upon to accomplish:

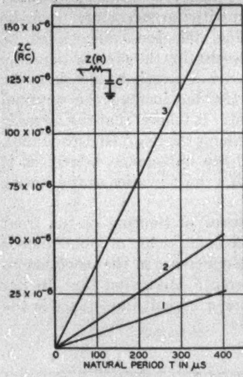

Fig. 5—*ZC* or *RC* Necessary to Reduce Turn, Coil, and Major Insulation Stresses Approximately to Same Values as Result From Uniform Distribution

1. For reduction of turn stresses. $t_2 = 0.2T$
2. For reduction of turn and coil stresses. $t_2 = 0.4T$
3. For reduction of turn, coil, and major insulation stresses $t_2 = 1.2T$

1. To slant the front of the wave to such an extent that the coordination gap will arc over at not less than 1 or 2 microseconds, which reduces the possible maximum amplitude and thereby reduces turn, coil, and major insulation stresses at the line end.
2. To reduce the turn stresses throughout the winding.
3. To reduce coil stresses throughout the winding.
4. To reduce major insulation stresses throughout the winding.
5. To reduce the amplitude of an incoming wave below the arcover value of a coordination gap or of line insulation at the station.

A minimum modification is required to accomplish the first, second and third degrees of protection. Maximum modification is required to secure the fifth degree.

From part I it follows that before a wave modifier can be designed it is necessary to know not only the rating but also the natural period $T$ of the transformer, or at least its maximum limit. Of course, a wave modifier designed for the longest natural period is perfectly satisfactory for transformers with shorter natural period but it is unnecessarily expensive.

Only the simplest of the very large number of possible wave modifying circuits are discussed here (Fig. 4).

### *Shunt Capacitance C Connected Between Line of Surge Impedance Z and Ground (Fig. 4A)*

This combination slants the vertical front of a long wave proportional to $ZC$.

The first degree of protection requires a capacitance of about 0.008 microfarads for a transmission line of 500 ohms surge impedance, assuming an impulse strength of transmission lines and rod gaps as originally published by Peek and in the recent paper on *Coordination of Insulation** by Messrs. Montsinger, Lloyd and Clem.

Values of $ZC$ to obtain the 2nd, 3rd and 4th degree of protection are given in Fig. 5, curves 1, 2 and 3, as functions of the natural period of the protected transformer.

To obtain the 5th degree a much larger value of capacitance may in general be required, except for very short waves (curve $C_1$, Fig. 6). (These calculations were made on the basis that the amplitude $E$ of the traveling wave is just below the value necessary to cause arcover of the average transmission line insulation.) If values of capacitance smaller than indicated by curve $C_1$, Fig. 6 are used, the coordination gap or line insulation near the station may arc over. This produces a sheer tail wave, which sets up high local stresses throughout the transformer windings of the same order of magnitude as those produced by a sheer front wave of the same amplitude. Thus the advantages gained by slanting of the front are nullified.

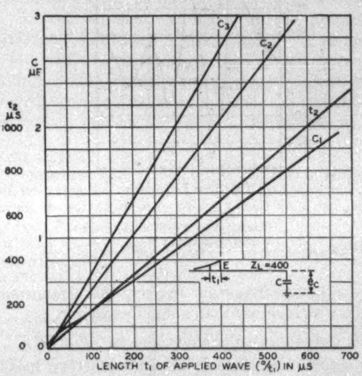

Fig. 6—Capacitance Required to Reduce Amplitudes of Traveling Waves

$C_1$ to prevent arcover of line insulation
$C_2$ all waves reduced to 60 per cent of their crest
$C_3$ all waves reduced to 50 per cent of their crest
$t_2$ time to reach crest when $C_2$ is used

A shunt capacitor may materially amplify internal voltages by entering into oscillation with the line in the case of the arcover of the latter. (Fig. 15, curves 1 and 3.)

### *Lightning Arrester and Shunt Capacitor*

It appears that this arrangement is the most satisfactory of all wave modifiers reviewed in this paper.

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*A.I.E.E. Trans., June 1933.

The front of the wave is slanted to the desired value by the capacitor and the surge impedance of the line. Its amplitude is limited to a predetermined value by the lightning arrester. The discharge of the capacitor through the arrester prevents a sheer tail wave from being impressed upon the transformer.

The combination of the arrester and the capacitor forms a non-resonating circuit. Oscillatory waves caused by an arcover of the line at any distance from the station are so modified in shape and amplitude that the hazard from them is reduced (Fig. 7).

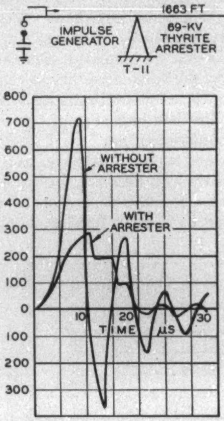


Fig. 7—Effect of Thyrite Lightning Arrester on Transmission Line Oscillations Caused by Line Arcover

Insulation at $T$—11 arcing over
Waves measured at $T$—14

In these two important respects this arrangement is far more satisfactory than a shunt capacitor.

*Series Inductance with Shunt Capacitor* (*Fig. 4B*)

A series inductance is an unsatisfactory means of protection for the following reasons:

As has been shown in previous papers,[1,2,11] a series inductance coil and the electrostatic capacitance of a transformer form an oscillating circuit capable of substantially increasing the voltage throughout the transformer winding as well as at its terminals. The use of choke coils has been abandoned on this account. To eliminate this danger the natural frequency of this circuit must be made of the order of 2,000 cycles or less. As the capacitance of an ordinary transformer is of the order of 0.0001 to 0.0004 microfarads the necessary inductance must be at least 15.6 henrys. This is prohibitive from the standpoint of the reactance it offers to operating frequency current. The permissible value ranges between 0.1000 and 0.0005 henrys for power transformers, depending on the transformer rating. If the inductance is limited to these values an external capacitor of at least 0.25 microfarads must be used, which is quite prohibitive except for low voltage circuits.

*Series Inductance Shunted with Resistance Combined with Capacitor Connected Between Transformer Terminal and Ground* (*Fig. 4C*)

The sheer tail waves that may be produced with a shunt capacitor can be eliminated by a series resistance $R$ (Fig. 4c). To reduce the voltage drop across such a resistance at operating frequency, a suitable inductance $L$ must be placed in shunt with the resistance. To make the circuit non-resonating, this inductance must be equal to at least $4R^2C$. Neglecting the effect of the surge impedance of the line, such a circuit would slant the wave proportionally to $4RC$ but increase the terminal voltage about 13 per cent. It follows that the larger is the resistance $R$, the smaller is the required capacitance, but the larger must be the inductance, which, as is shown by the equation $L = 4R^2C$, varies as the second power of the resistance.

The choice of the degree of slanting of the front determines $RC$. The maximum value of inductance is limited by the permissible increase in the reactance to operating frequency current. Assuming that 10 per cent of the transformer short-circuit inductance is the limit for the protective inductance, its kilovoltampere rating would range from approximately 0.5 to 1.5 per cent of the transformer capacity of the station. This means that it may be quite large in size in case a large transformer installation is to be protected. Its range, measured in henrys, is from 0.005 to 0.1000.

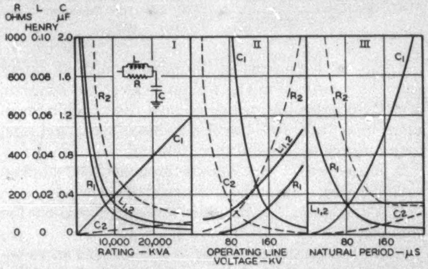


Fig. 8—Constants of Wave Modifier as Affected by Kva Rating, Operating Line Voltage and Natural Period of Protected Transformer (Surge Impedance of Transmission Line is Neglected)

$R_1C_1L_1$ required for reduction of major insulation stresses (curve 4, Fig. 1)
$R_2C_2L_2$ required for reduction of coil insulation stresses (curve 3, Fig. 2)
I—Line voltage 138 kv, natural period 100 μs
II—Rating 10,000 kva, natural period 100 μs
III—Rating 10,000 kva, line voltage 138 kv

Thus with $RC$ and $L$ determined as above, the value of $R$ and $C$ can be found from the relation $L = 4R(RC)$. Values of $R$ and $C$ necessary to protect transformers of different rating vary, of course, over a wide range, Fig. 8 shows the relation between $L$, $R$ and $C$ of a modifier and the natural period, kilovoltampere and operating voltage of transformers.

In the above method of determination of $L$, $R$ and $C$, the surge impedance of the line was completely neglected. This is believed to be a justified conservatism as the effective value of the surge impedance is often not known and also because in the case of transmission line oscillation its beneficial effect is not sufficient.

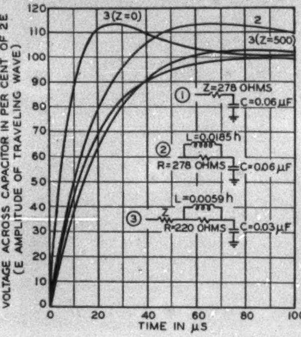


Fig. 9—Wave Fronts Across Capacitors of Various Wave Modifiers Produced by a Traveling Wave with Sheer Front and Long Tail

In case it is desired to place dependence on the surge impedance $Z$ of the line the procedure for determination of $L$, $R$, and $C$ is modified. First the value of $C$ is determined from the product of $CZ$ which in itself is determined by the degree of protection desired: $L$, as before, is determined by consideration of the reactance it offers to power current. To make the modifier itself non-resonating, $R$ is calculated from the equation $L = 4R^2C$. The calculation shows that if the surge impedance can be depended upon smaller values of $C$ and $L$ can be used without an appreciable change in $R$. (See Fig. 9.) Thus less expensive wave modifiers may serve the required purpose.

Current limiting reactors in series with incoming lines may be made a part of a wave modifier. In such a case they must be shunted with the proper resistance and a suitable capacitor must be connected between transformer terminal and ground.

*Protective "Transformers" (Figs. 4D and 4E)*

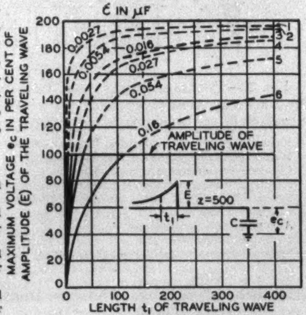
Instead of placing resistance in shunt with the inductance as was done in the previous type of modifier, the inductance and the resistance can be replaced by a transformer with its secondary winding closed through a resistance. The tank of the inductance coil can be made to serve as such a closed-circuit secondary winding.[7,12,13,14] The equivalent circuit of such a "transformer" with the capacitor $C$ is shown in Fig. 4E. Such an arrangement may be made to produce results similar to the previous type, but it is more difficult to make its action non-oscillatory due to the presence of $L_1$ and $L_2$ (Fig. 11, curves 1 and 4). In addition to the resistances and inductance the protective "transformer" has inherent capacitance $C_i$ between the high voltage winding and the grounded tank. This capacitance is not shown in Fig. 4E. In oil-immersed units it is of the same order of magnitude as that of a power transformer (of the order of 0.0001 to 0.0004 microfarads) and therefore impotent to render protection.

Extensive tests were made on such a device designed for a 22-kv circuit. Due to the relatively low circuit voltage, this device had solid insulation. As stated by the manufacturer, dependence was placed entirely upon the inherent capacitance, eddy losses, and the inductance of the coil inclosed in a specially designed grounded metal casing. The casing was so designed as to give the maximum possible capacitance (measured value found to be approximately 0.0034 microfarads) between the winding and the casing and the maximum eddy loss. Figs. 11 to 15 inclusive give some of the results of this study which confirm the theoretical conclusions.

Analysis indicates that it would be quite out of the question to obtain any material benefit from such a "transformer" if the additional capacitor $C$ were not used, because inherent constants of the protective "transformer" (indicated by ($A$), Figs. 11 to 15 inclusive) attainable in practise are such that it forms an oscillatory circuit with the transformer to which it is connected. Such a device would have the undesirable features of an inductance coil, *i.e.*, the stresses at the line end (Fig. 11, curve 4; Fig. 14B) and throughout the transformer (curves 4 of Figs. 12 and 13; Fig. 14B) may appreciably be increased when a unidirectional or an oscillatory surge is applied.

Fig. 10—Maximum Terminal Voltages on Transformers that are Protected by a Capacitor Selected (From Fig. 5) to Reduce

1, 4 turn stresses
2, 5 turn and coil stresses
3, 6 turn, coil and major insulation stresses
1, 2, 3 natural period of transformer is 20 μs
2, 4, 6 natural period of transformer is 200 μs



Arcover of the line or of the bushing of the device may cause stresses (especially between turns and coils) at least of the same order as if the device were not present (curves 5, Fig. 13). In the case of line arcover at a distance from the station, the line is set into oscillation and the internal stresses may be amplified appreciably by such a "transformer" as shown by comparison of curves 1 and 2 of Fig. 15. Unless the waves are extremely short, the internal voltages to ground would not be reduced by such a modifier (curves 1 and 3, Fig. 12), but may be increased in case the line surge impedance is insufficient (curves 4 of Figs. 12 and 14).

On account of these phenomena it would be quite impossible and often misleading to judge the overall protective value of such a device by its reduction of coil or turn stresses at the line end of a transformer. The combination of the *line surge impedance*, the inductance of the protective "transformer," its ground capacitance $C_i$ and ground capacitance $C_t$ of the transformer may form a non-oscillatory circuit for a single unidirectional impulse. The sheer front of an incoming traveling wave will be slanted then at the transformer terminal to approximately $t_2 = 3Z\,(C_i + C_t)10^6$ microseconds compared to $t_2 = 3ZC_t\,10^6$ microseconds when the protective "transformer" is not used. Thus if $C_i = C_t = 0.0003$ microfarads and $Z = 500$ ohms, $t_2 = 0.45$ microseconds without the device or 0.90 microseconds with the device. The effect upon the transformer of this small increase in slanting of the wave front is negligible. This, however, is the only possible beneficial effect that could be expected from such a protective transformer, as it can not reduce the amplitude of a flat top wave longer than 0.90 microseconds. If $C_i$ is increased even ten-fold by the substitution of oil with solid insulation then the front will be slanted only to some 5 microseconds. Such a front reduces appreciably stresses between turns and coils near the line end of transformers with short natural period, and very little in transformers with long natural period: (curves 1 and 3 of Fig. 13 I and II).

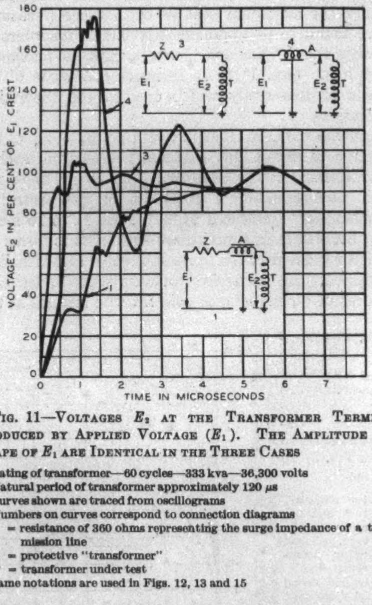


FIG. 11—VOLTAGES $E_2$ AT THE TRANSFORMER TERMINAL PRODUCED BY APPLIED VOLTAGE ($E_1$). THE AMPLITUDE AND SHAPE OF $E_1$ ARE IDENTICAL IN THE THREE CASES

Rating of transformer—60 cycles—333 kva—36,300 volts
Natural period of transformer approximately 120 $\mu s$
Curves shown are traced from oscillograms
Numbers on curves correspond to connection diagrams
$Z$ = resistance of 360 ohms representing the surge impedance of a transmission line
$A$ = protective "transformer"
$T$ = transformer under test
Same notations are used in Figs. 12, 13 and 15

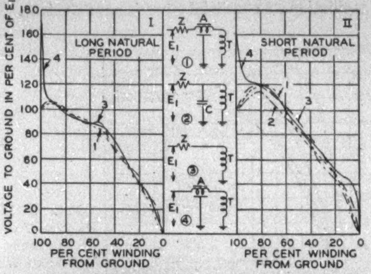


FIG. 12—ENVELOPES OF MAXIMUM VOLTAGE TO GROUND THROUGHOUT TRANSFORMERS RATED

I—60 cycles, 333 kva—36,300 volts—2,300 volts. Natural period approximately 120 $\mu s$
II—60 cycles, 8,000 kva—36,300 volts—12,100 volts. Natural period approximately 29 $\mu s$
Unidirectional impulse applied
Numbers on curves correspond to connection diagram

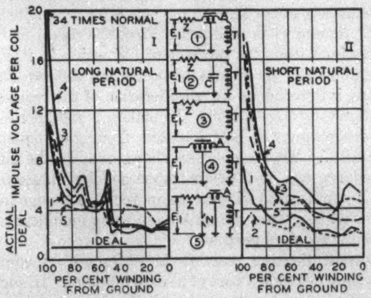


FIG. 13—MAXIMUM VOLTAGE ACROSS COILS OF TRANSFORMERS RATED

I—60 cycles—333 kva—36,300 volts—2,300 volts. Natural period approximately 120 $\mu s$
II—60 cycles—8,000 kva—36,300 volts—12,100 volts. Natural period approximately 29 $\mu s$
Capacitor $C$ = 0.0034 $\mu f$ equal to inherent impulse capacitance $C_i$ of protective transformer $A$. Unidirectional impulse applied. Numbers on curves correspond to connection diagrams

Analysis shows that better protection, although still too small to be of practical importance, is secured where such a device is replaced by a capacitor (connected between line and ground), the capacitance of which is made equal to the inherent ground capacitance $C_i$ of the device. Test results substantiate this conclusion (curves 1 and 2 of Figs. 12, II and 13, II).

## Part III

### DESIGN CONSIDERATIONS

As has been shown, the analytical solution of the above wave modifiers for any transformer of known transient voltage characteristics can be determined without much difficulty. It is more difficult, and in most cases impossible, to make a practical design of a modifier that can compare, from an economical standpoint, with the internal means of obtaining the necessary security from transient voltage hazards. As a modifier is an auxiliary equipment, its safety factor must be made greater than that of the protected apparatus.

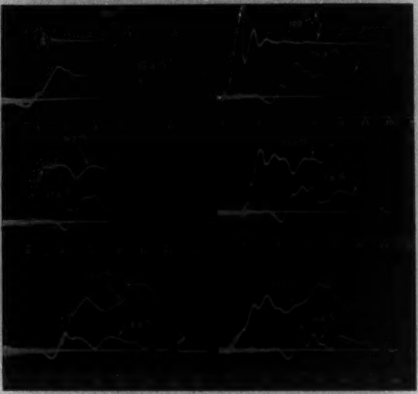


FIG. 14—VOLTAGES MEASURED FROM VARIOUS POINTS OF THE TRANSFORMER WINDING TO GROUND

(Left) Transformer directly connected to impulse generator

(Right) Protective transformer connected between transformer and impulse generator

Transformer neutral grounded. Rating of transformer—60 cycles—8,000 kva—36,000 *Y* volts—12,100 volts. Natural period approximately 29 microseconds

Numbers on oscillograms give distance of point from neutral in per cent of the total length of the winding. 100 per cent is transformer line terminal. Abscissa gives time in microseconds. Note the amplification of one of the transformer harmonics by the protective transformer

*Resistance.* This part of the device presents no practical difficulty in most cases.

*Capacitance.* The range in capacitance required for transformers above 3,000 kva and 66 kv is as follows:

For the protection of coil insulation from 1.4 to 0.001 microfarads.

For the protection of major insulation from 12 to 0.008 microfarads.

The most economical capacitor available at present is of the pyranol filled, hermetically sealed type used for power factor correction. Fig. 16 was prepared to give an idea of the physical size of such a capacitor. This figure gives the volume only of the active material of a capacitor. The overall volume perhaps would be twice as large.

The volume of a capacitor with insulation such as is used in transformers and oil immersed reactors would be about 150 times greater than that of the pyranol capacitors. This means, for example, that the volume of actual insulation (between plates) of the smallest capacitor that could be used for the protection of the major insulation of a 230-kv transformer is 1,250,000 cu in. (108 by 108 by 108 inches) which is equal to the volume of a 230-kv transformer of about 5,000 kva capacity.

These figures are perhaps the best answer to the question of whether it is possible to secure the necessary capacitance in a modifier by means of the inherent capacitance $C_i$ of an inductance coil to its tank and ground shield (a metal cylinder placed inside the coil and connected to the tank). Calculations show that the maximum capacitance of a practical size oil-immersed coil to its tank and ground shield is of about the same order of magnitude as that of an ordinary transformer winding to ground (0.0001 to 0.0004 microfarads).

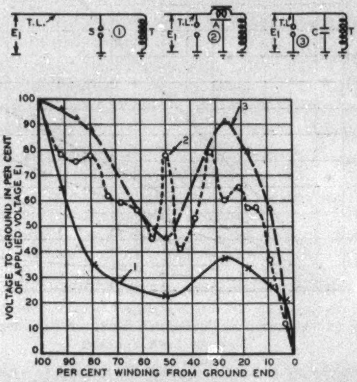


FIG. 15—AMPLIFICATION OF STRESSES IN TRANSFORMERS BY IMPROPERLY DESIGNED MODIFIERS IN CASE OF OSCILLATIONS CAUSED BY ARCOVER OF THE TRANSMISSION LINE

Transformer rated 60 cycles—8,000 kva—36,300 Y volts—12,100 volts. Natural period approximately 29 microseconds

Unidirectional impulse applied over transmission line (T.L.) of 2 miles in length. Sphere gap located 600 ft from transformer and set to arc after the wave is reflected from the transformer terminal. Note the substantial increase in voltage due to the presence of the protective transformer (curve 2) and the capacitor (curve 3)

Numbers on curves correspond to connection diagrams

*Inductance Coil.* The design of the inductance coil for a wave modifier must, of course, comply with the established practise for high voltage windings used in power circuits. This means that the coil should be able to withstand forces and heating under short circuit, and transient voltage stresses limited only by the arcover of the coordination gap or of the bushing of the modifier. Its losses due to the flow of the normal load current must be only a small fraction of the transformer "load loss."

Consequently, the inductance coil can be looked upon as a part of the line end of the transformer winding placed outside of the transformer proper, and therefore it presents to a designer essentially the same group of problems as does a transformer winding. From an engineering standpoint, therefore, it is rather questionable whether the overall safety factor of the inductance coil of a wave modifier, together with the transformer, can be made greater than that of the transformer alone. Thus such a modifier in the best case, *shifts* merely the high transient voltage stresses from the transformer winding to the modifier winding.

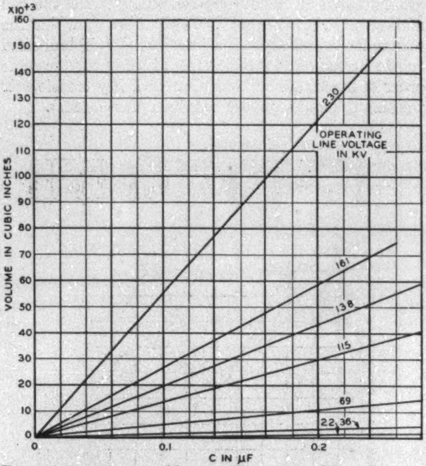


FIG. 16—APPROXIMATE MINIMUM VOLUME OF CAPACITORS FOR VARIOUS LINE VOLTAGE

Scale for volume applies to capacitors when used in systems with grounded neutral. When capacitors are used in systems with isolated neutral, multiply values by 1.51

## CONCLUSIONS

1. The internal stresses in ordinary transformer windings are very severe because of the high amplitude of lightning voltages on transmission lines and of the extremely non-uniform distribution of this voltage throughout the winding.

2. Practically these stresses, except those from winding to ground at the line end, can be reduced to a far greater extent by making the voltage distribution throughout the winding uniform, than by reduction of the amplitude of the applied voltage. This is particularly so for turn and coil stresses. (See Table I.) However, the reduction in the amplitude of transient voltages below those found on transmission lines is very important and desirable for all transformers. It is imperative for most transformers, built before the principle of coordination was generally accepted.

3. *Gaps.* Coordination rod gaps establish an impulse voltage level as a basis for design and testing. Transformer strength must be above that level while maximum voltage permitted by a protective device must be below it. Such a gap when installed near transformers reduces the maximum voltage some 10 or even 20 per cent below that permitted by an average station insulation.

Although a rod gap has serious limitations as a protective device, it should be looked upon as the last line of defense for transformers and station, and used irrespective of the presence of protective means.

4. *Lightning Arresters.* To secure an added safety factor of protection over that given by a standard setting of the coordination gap, and at the same time eliminate outages at the station, the standard lightning arrester is the best solution for the following reasons:

(*a*) It reduces stresses to from 30 to 75 per cent of those permitted by the standard coordination gaps, depending upon wave shape and whether the system is grounded or isolated. The steeper and shorter the wave, the greater the relative reduction by the arrester as its impulse ratio is practically unity.

(*b*) It prevents outages at the station.

(*c*) The choice of its constants and transient voltage characteristics is independent of the natural period of the transformers.

(*d*) The simplicity of its function permits the necessary sturdiness of construction and assures positiveness of action.

(*e*) A rod gap set to give the same protection against 0.5/5 or 1.5/40 waves, as given by the thyrite arrester for grounded systems, would cause outages from many switching surges.

(*f*) It carries no operating frequency current. This is advantageous for two reasons: (1) The design is not complicated by the consideration of short-circuit stresses, normal and short-circuit heating, losses, reactance, etc., that are present in the design of series protective devices. (2) It does not add loss or reactance to the system.

5. *Voltage Distribution Control.*

(*a*) Essentially uniform voltage stresses within transformer windings theoretically speaking, can be secured either by external devices modifying the applied wave so that its front and tail are sufficiently slanted, or by proper electrostatic shielding of the windings, which eliminates the cause of non-uniform voltage distribution.

(*b*) *External Means.* The wave modifiers may consist of resistance, capacitance and inductance (Fig. 4C) or of capacitance in shunt with a lightning arrester.

The constants of the "modifier" must be such that voltage at the transformer terminal is non-oscillatory when an impulse is applied directly to the modifier without intervening transmission lines.

To obtain the desired reduction in stresses, the length of the front wave produced at the transformer terminal by a sheer front wave applied to the modifier, must bear a definite relation to the length of the natural period of the transformer.

In a properly designed modifier (Fig. 4D) the necessary values of constants are such that they can not be secured inherently in a specially designed oil immersed reactance coil without making it of utterly impractical dimensions.

Tests and analytical studies show that the capacitance to ground $C_i$ of such a modifier (in combination with the surge impedance of the transmission line) is its only beneficial feature. The effect of its high frequency resistance is not sufficient to prevent resonance between the modifier and the transformer. For these reasons better and more positive results are obtained with a plain capacitor of the same capacitance $C_i$, connected between the line and ground. With constants that can be secured in such a coil in practise, the device is either useless or harmful. (Curves 1, 4 and 5, Figs. 12 and 13.)

In a modifier of the type shown by Fig. 4C, the inductance coil presents the same design problems as does a transformer winding, and the capacitor becomes quite large in size, even in the case of the most effective use of its insulation, as is accomplished in pyranol capacitors. (Fig. 16.)

Even an improperly designed modifier may appreciably reduce stresses between turns and coils at the line end of the winding under certain favorable conditions, due to the effect of the surge impedance of the transmission line. However, at the same time it may materially increase turn, coil, and major insulation stresses in other parts of the winding as has been shown. On this account the reduction of stresses obtained at the line end can not serve as the criterion of the overall protective value of such a modifier.

The most practicable solution, in the case of an ordinary transformer where it is desired to use a wave modifier, is offered by a capacitor in shunt with a lightning arrester, because this type of modifier not only slants the wave but also materially reduces its amplitude. The size of the capacitor depends on the degree of protection desired.

(*c*) *Internal Means.* A radical reduction of turn and coil stresses at the line end of a winding can be obtained much more economically by means of a small electrostatic shield, internal to the transformer, than by any external device.

Electrostatic capacitance of a non-resonating transformer is many times that of an ordinary transformer and is of the order of 0.001 to 0.004 microfarads. The combined effect of the surge impedance of the line and of this capacitance slants a sheer wave front to 1.5 and 6.0 microseconds, respectively. It therefore reduces the crest voltage of exceedingly short waves, particularly where several transformer banks are installed.

A wave modifier that does not radically reduce the amplitude of an incoming surge, but produces essentially uniform voltage distribution throughout a transformer winding, is impracticable in comparison with non-resonating transformers for the following reasons: It requires for each phase two bushings, a capacitor, reactor, resistor, tank and oil. It also requires a special mechanical support or foundation, and extra space in the station; while in a non-resonating transformer the uniform distribution is obtained by a simple electrostatic shield internal to the transformer.

In an ordinary transformer protected even with a proper wave modifier the voltage distribution depends on the amplitude, length and shape of the incoming surge and whether it is unidirectional or oscillatory. The voltage distribution in a non-resonating transformer is independent of these factors.

Where it is desired to employ an external protective device for the protection of either an ordinary or a non-resonating transformer, a properly designed lightning arrester is superior to the best wave modifier.

Minimum internal voltage stresses are secured where a transformer, designed to give uniform voltage distribution, for waves of all shapes, is protected with a properly designed arrester. Such an installation is the most practical and reliable.

The authors gratefully acknowledge the value of the criticism given by their colleagues, Messrs. P. L. Alger, A. N. Garin and W. A. McMorris during the preparation of the paper.

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## Discussion

**K. B. McEachron:** Although the authors discuss the use of various protective schemes as related to power transformers, this discussion presents some data concerning the operation of some of the devices mentioned when applied to distribution transformers.

One phase of the subject which should be generally appreciated, but apparently is not, is given in the following. It is commonly supposed that the only method that does not involve structural changes in the transformer itself is to decrease the steepness of the wave front, by the use of some sort of wave modifier. A little consideration will show that reduction of amplitude may accomplish the same purpose. To illustrate, if the amplitude is reduced to zero, obviously the turn stresses will be zero, similarly the rate of rise also will be zero.

To illustrate this feature of arrester protection consider some tests made recently in Pittsfield in which the protective transformer of the type described by Messrs. Palueff and Hagenguth was employed. Two of these devices designed for internal mounting in a distribution transformer rated 10 kva, 2,300/4,000 *Y* volts 60 cycles were tested.

With a line of 500 ohms surge impedance and a 25-kv traveling wave of sheer front the potential measured across 5 per cent of the winding from the line end was twice as high with the wave modifier as it was with a standard intershunt thyrite arrester. The potential with the modifier was found to be the same as when a 0.001-$\mu f$ capacitor was connected between the transformer terminal and ground.

With 1,200 ft of distribution circuit connected between the impulse generator and the test, and a 50-kv traveling wave with sheer front, the potential across 5 per cent of the transformer winding on the line end was 26 kv with the wave modifier, 17 kv with a 0.002-$\mu f$ capacitor, 8.2 kv with the thyrite intershunt arrester and 16 kv with a pellet arrester plus a 50-ohm ground resistance.

In general where the ratio between the impulse strength of the line insulation and the arrester potential is as great as in the case of distribution voltage apparatus the arrester not only reduces the stress in the major insulation to ground but also will reduce the stress between turns and sections, compared to that which would have been present without the arrester or with the use of the modifier tested.

**V. M. Montsinger:** The writer emphasizes one point mentioned but not discussed to any great extent in the paper, that is the question of protection of the wave modifiers against lightning; also, the question of the proper insulation level for a protective device of this kind.

Some of the sketches given in Fig. 4 show inductive elements or windings similar to transformer windings. It is obvious that such a winding having turns insulated similar to a transformer presents a problem in protecting these turns against lightning quite similar to the problem of protecting transformer windings. It was shown in a recent paper[1] that the margin of safety in a transformer winding decreases as the impulse wave becomes steeper when the impulse voltage is limited by either line insulation or by a rod gap. The same thing is true for the winding in a wave modifier. The claim may be made that these modifiers slope the wave front and thereby protect themselves. This is not possible because only the wave leaving the modifier is affected by its capacitance. Therefore, the problem of protecting against all lightning waves is quite similar. Unless these modifiers have a substantial higher level of insulation than the transformer being protected it is a case of where the protecting device requires the same degree of protection as the apparatus it is protecting.

It has been common practice to insulate and test protective devices for a higher insulation level than the apparatus being protected. It is logical therefore that these wave modifiers should be given a higher impulse test than a transformer of the same voltage rating.

**E. T. Norris:** The greater part of the paper is devoted to the condemnation of "wave modifiers"—a term which may be presumed from the technical references and from the description of actual tests in the body of the paper, to mean in particular the Ferranti surge absorber. The authors object to the term "absorber" on the ground that it does not absorb energy. Without debating the technical accuracy of this statement, it must be pointed out that the word "absorb" has no essential connection with energy.

The surge absorber is a device connected in the line so that a surge or traveling wave must pass through it before reaching station apparatus. In the process the device absorbs the venom and deadliness of the surge as regards damage to station apparatus, and therefore, is appropriately termed "surge absorber."

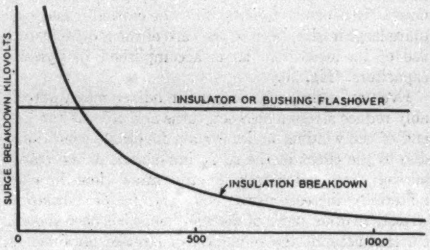

FIG. 1—EFFECT OF NUMBER OF SURGES ON INSULATOR FLASHOVER AND SOLID INSULATION BREAKDOWN

It is not claimed that surge absorbers greatly reduce the amplitude of a surge under all conditions. Much stress has been laid on the control and reduction of the amplitude of a surge in the effort to obtain adequate protection of apparatus and to prevent interruptions to the supply. This assumption that decrease in the amplitude of a surge is necessary to secure protection is not supported by operating experience, and does not bear examination by analysis of technical characteristics.

Operating experience the world over shows that damage due to the breakdown of the main insulation of transformers is extremely rare. This can only be explained on the basis that the surge dielectric strength is such that it will withstand a large number of the most severe surges permitted by standard line insulators.

While the stresses between live parts of electrical apparatus and ground are definitely limited by the amplitude of the surge, which in turn is limited to safe values by the line insulation, the voltage gradients or stresses between turns of parts of the windings of inductive apparatus may reach thousands of times normal values. Since breakdown of solid insulation, such as interturn insulation, depends upon the number of surges, as shown in Fig. 1, it would be expected that in service the rate of complete failure of transformers due to lightning would be greater for the older transformers. This has been confirmed often by operating experience. The rate of burnouts reproduced in Fig. 2 from the A.I.E.E. TRANSACTIONS, Volume 51, page 256, illustrates this fatality rate. The death rate of any apparatus subject to wear and tear varies with age in a similar manner.

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[1] *Coordination of Insulation,* by V. M. Montsinger, W. L. Lloyd, Jr. and J. E. Clem, A.I.E.E. TRANS., June 1933, p. 417.

It is well known that a choke coil of very large inductance connected in series with the line may materially flatten the wave front of an incoming surge. It also is established that a condenser connected between the line and ground may give excellent protection. The serious objection to both of these items is that they are likely to enter into combination with capacity or inductance in the adjacent circuit, such as a transformer bushing, or a short length of line, and form a local oscillatory circuit. If the incoming surge happens to be of the same equivalent frequency as this oscillatory circuit, excess voltages will be produced, which will make the effect of the protective inductance or capacity worse than if it had been omitted altogether. The surge absorber may be looked upon as including the advantages of a large inductance and capacity. The disadvantages are obviated by making the combination aperiodic through the inclusion of a large loss or resistance component. This loss component consists of the secondary winding or dissipator of the absorber which is the seat of eddy current and resistance losses. Analysis of a wide range of oscillograph studies has failed to show any evidence of resonance under any conditions encountered under normal operation.

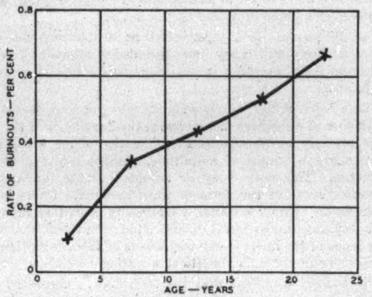

FIG. 2—RELATION OF AGE OF TRANSFORMERS AND BURN-OUT DUE TO LIGHTNING

The percentage absorption of the absorber is consistently high for surges of all magnitudes and wave forms, whereas the percentage absorption of a choke coil varies periodically from positive to negative values showing that the choke coil may even do more harm than good, depending upon the type and magnitude of the surge and the oscillation characteristics just described.

The wide variation in the natural causes of surges makes it difficult to determine the reduction in stress due to protective apparatus in any particular case, with the result that positive evidence as to the effectiveness of any device is extremely difficult to obtain and requires many years of operating service. A single report of a particular installation that no trouble has been experienced since surge absorbers were installed, is unimportant evidence, but the large number of such reports that have already been received from all parts of the world and under all kinds of operating conditions, become very positive and definite evidence indeed.

Any protective device or lightning arrester which after years of operation still has to depend upon calculations and experimental data for evidence of its effectiveness, should be regarded with suspicion. The proofs given by operating experience of the satisfactory operation of absorbers, are that in each case before the absorbers were installed considerable trouble from lightning surges was experienced, whereas after the installation the troubles ceased. In many such cases surge absorbers have replaced discharge type arresters. The only instances on record of a surge absorber apparently failing to protect, have been causes of misapplication. No instance has been recorded of failure of surge absorbers to give complete protection within their sphere of action.

A further indication of the satisfactory operation of absorbers has been the large proportion of repeat orders. In many cases a supply company will place its first order as a trial installation, and wait for a year or so of operating experience before deciding whether or not to install more absorbers. A recent analysis of all surge absorber users with operating experience of one year or more (that is, one lightning season) shows that 67 per cent already have placed repeat orders. Many of these users were, however, private concerns or manufacturers taking electricity from a supply company, and therefore having no occasion to place repeat orders. Restriction of the analyses to power supply systems and distribution companies who probably are all in a position to extend absorber installations, shows that in 78 per cent of these cases repeat orders for absorbers have been placed.

These figures are a practical proof of the satisfactory operation of surge absorbers, and contrast strongly with operating experience with lightning arresters as shown by the following extract from *Electrical Engineering* for June, 1933, page 394. Seventeen operating companies representing approximately 34 per cent based upon output of the electric power industry in the United States, reported on their experience with lightning arresters. Of these 17 companies, "10 express considerable dissatisfaction with present day arresters, 9 state that the arresters have insufficient protective ability to reduce over-voltages below insulation levels, as indicated by equipment failures." The paper is confined to the effect of protective devices on transformer stresses.

Operating experience has shown clearly that the surge absorber is very effective in preventing the blowing of high tension fuses due to lightning surges.

Claims for the operation and effectiveness of the surge absorber have hitherto been confined to the protection of transformers and other inductive apparatus from breakdowns between turns and coils due to the steep wave front characteristics of a lightning surge. Shortly after the first absorbers were put into operation, operating reports were received indicating greatly improved line operation since the installation of the absorbers. These reports were at first put down to coincidence, but they continued to arrive in increasing numbers, and are now sufficient to rule out coincidence or chance, and to indicate that the absorber has important effects in this connection. It is now established that surge absorber installations greatly reduce the number of line flashovers and line interruptions, and improve the operating stability of the line.

These characteristics of the surge absorber in greatly reducing interruptions to the continuity of supply due to line flashovers, and to the blowing of primary fuses in conjunction with its proved protective action preventing damage to inductive apparatus, show that it is providing a safe and effective solution to the surge protection problem. Moreover, in giving this protection and reliable operation it does not attempt to discharge the surge to ground with consequent power arcs and disturbance to the supply system.

**D. W. Roper:** Messrs. Palueff and Hagenguth state: "Where it is desired to employ an external protective device for the protection of either an ordinary or a non-resonating transformer, a properly designed lightning arrester is superior to the best wave modifier." All of the transformers on the distribution system of the Commonwealth Edison Company are of the ordinary type and the number of fuses blown during lightning storms averages about 2.5 times the number of transformers burned out. The blowing of the fuses principally is due to arcing across porcelain bushings or across air spaces within the transformer. This arcing is due to the maximum transient voltage and not to the shape of the wave. When the results obtained with different types of arresters are compared, it is found that the smallest percentage of fuses blown corresponds to those types of arresters that limit the maximum transient voltage to the lowest value.

In the year 1932 the interconnection between the transformer secondary neutral wire and the lightning arrester ground wire, as recommended by Messrs. Harding and Sprague,[2] was applied to about 5,700 transformers. This interconnection resulted in a reduction of the maximum transient voltage without altering the shape of the transient, and this has resulted in a reduction of 65 per cent in the percentage of the transformer troubles due to lightning.

The 5,700 distribution transformers with the interconnection between lightning arrester ground and the transformer secondary neutral have now been in service for one year. During that time the failures on these transformers have been as follows:

| | |
|---|---|
| Burning of primary leads | 3 |
| Failure of insulation between primary and secondary coils | 4 |
| Failure between turns on primary winding | 1 |
| Total | 8 |

If the surge absorber is a better device than the lightning arrester, then it must afford some additional protection beyond that provided by the lightning arrester. If it does not reduce the maximum voltage of the lightning transient, it would not eliminate the 3 failures due to the burning of the primary leads nor the 4 failures due to breakdown of the insulation between primary and secondary windings. The only failure that would have been eliminated according to the claims of the makers of the device would be the one transformer which broke down between turns in the primary winding. Would it be economical to install 5,700 surge absorbers, which cost more than twice as much as the lightning arrester, when the most that we could hope for would be to save one transformer failure?

It should be noted that the transformer failure record since the 5,700 interconnections were installed has been about 1/7 of 1 per cent, and further, that the age of the transformers that failed ranged from 9 years to 30 years, with an average of 19 years. This appears to indicate that with the modern types of transformers which are built to withstand a transient voltage test, the present scheme of lightning protection used in Chicago would be practically perfect.

The surge absorber has been criticized because the makers adopted a name which, after test, has been found to be a misnomer. But is the name any more of a misnomer than the term "lightning arrester?" One device does not absorb the surge, and the other device does not arrest the lightning. As the A.I.E.E. is now in the midst of a campaign to adopt a list of standard terms and definitions, why should it not consider adopting a name for the lightning arrester that is not a misnomer? The German term "blitzableiter," which means lightning diverter, appears to be far more appropriate. The approval by the A.I.E.E. of the continued use of the term "lightning arrester," which is a misnomer, leaves the field open to the makers of other devices to use a misleading trade name for the device, that is, a name that is quite foreign to its properties, and then sell the device to the unsuspecting on the basis of the name.

**C. S. Sprague:** The authors bring out the point that the flashover of a rod gap may introduce stresses fully as serious as those caused by the wave itself. The writer agrees with the authors, in that the rod gap, or possibly a specially designed bushing or gap in the case of small transformers, should be used as a last line of defense in conjunction with suitable arresters.

The reduction of internal stresses by the use of wave modifiers, or internal shielding, usually is expressed relative to the stresses produced by a steep front wave. It should be remembered that in practice the large majority of waves which reach the transformer will have suffered attenuation, and the actual reduction in turn stresses due to the protective equipment may not be as large as anticipated.

**J. M. Thomson:** The writer is particularly impressed with the authors' statements in recognition of the reduction in transformer turn and coil stresses, resulting from the sloping of the wave front by means of some form of wave modifier—particularly their statement that "a very substantial reduction of internal stresses in transformer windings can theoretically be accomplished by proper modification of the incoming traveling wave, without changing its amplitude." The possibilities of stress reduction by this means are very clearly defined in their tabulation, comparing the relative stresses in grounded neutral and in isolated neutral transformers.

Our own investigations and experience have indicated that the turn stresses that normally cause the vast majority of transformer failures from lightning and switching surges, can be reduced to safe limits by a wave modifier, without excessive cost, except possibly for the higher voltages. The writer's company has placed in service 3,000 or more wave modifiers, many of which have been installed to replace other forms of protective equipment that had failed to give protection: yet although there have been one or two isolated instances of failure in the absorbers themselves, we have yet to hear of a failure from lightning in any transformer winding protected by this device.

The authors in their paper make particular reference to a device of this sort. They have included a number of curves based on their test of this device under normal and special conditions.

Curve No. 1 in Fig. 11, showing the effect of a wave absorber under normal conditions in series with the impedance of the line, gives not only an all-important modification of the wave front, but a slight reduction of amplitude, without any evidence of resonance. This curve may be accepted as the fundamental corrective curve of this form of wave modifier. Curve No. 4 in the same figure represents a laboratory condition in which the transformer under test is disassociated from the normal surge impedance of the line. Oscillatory waves of this description will not be encountered under practical operating conditions.

The authors comment that the term "wave absorber" is a misnomer, due to the relatively small energy absorption in any device of this sort. This criticism of the absorber nomenclature is perhaps justified, but the small absorption that does occur as eddy loss in the dissipator plates, serves undoubtedly to minimize any tendency toward resonant conditions.

In order that the authors' suggestion with respect to resonance may not carry too much weight in opposition to our own investigations, I might add that the oscillograms taken in independent studies in Germany and in the United States, have confirmed our findings that the wave absorber does not introduce resonance under any normal condition of operation.

The authors make specific reference to the limitation of distributed capacitance obtainable in the normal construction of the special inductive wave modifiers. The values of capacitance which we actually obtain approximately are 10 times as high as the figure that is used in the paper. Where still higher capacitance values are required for amplitude reduction, as in the case of generator protection, it is quite possible that economic factors would make it advisable to supplement the maximum obtainable distributed capacity by adding lumped capacitance.

The authors stress the size and space factor of wave modifiers sufficient to afford protection to the transformer. Our standard design practice calls for sizes even larger than those indicated, and this fact in itself explains why a wave modifier, to give complete transformer protection, cannot under present conditions compete on a price basis with any of the various forms of discharge arrester, except in the lower voltages. Consequently the use of wave modifiers will be justified only in those cases where the extra cost of assured protection is warranted by the operating conditions.

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[2] *Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main*, A.I.E.E. TRANS., March 1932, p. 234.

**F. J. Vogel:** The subject of lightning protection of transformers is, at last, largely a question of a knowledge of the surge strengths and electrical performance of the various parts of the circuit, and also of the economics of the situation.

There is no question that transformers as built and surge tested today have a well defined insulation strength against surges and that this can be demonstrated as above the present recommended coordinating gaps for all except direct strokes or very high surges of very short duration. This limitation of the coordinating gap can be avoided by the use of ground wire protection if carefully applied, but such application may not always be considered economical. The use of other forms of coordinating gaps is possible but gaps alone have the serious disadvantage of power flow and a service outage.

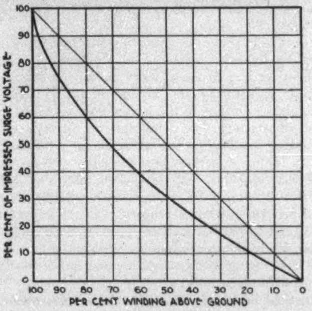


FIG. 3—REPRESENTATIVE INITIAL VOLTAGE DISTRIBUTION OF SINGLE GROUP SHELL TYPE TRANSFORMER

On the other hand, the modern arrester results not only in a much lower protective level, but prevents service outages. Even yet some protection against direct strokes will be required if all outages must be avoided.

Besides these two methods of protection, another means, sloping the front of the surge has been advocated. If the front of any surge be sufficiently long, a nearly uniform voltage distribution will be obtained within the transformer winding. The idea back of this is that transformer failures are the result of high turn-to-turn or coil-to-coil stresses exclusively. The question to be answered is whether such sloping can be obtained and utilized economically, and, even so, if there are not other disadvantages which render it impractical to do so.

The writer discusses several cases with a view of illustrating some limitations of such devices. One case is that of the shell type of transformer. The initial distribution of voltage for such a transformer with a single high voltage group is shown by Fig. 3. With 10 coils in the high voltage winding, 40 per cent of the surge voltage will occur between the first two coils. With such designs, the most that could possibly be gained, by sloping the wave front, would be to reduce the stress to about 50 per cent of that with the steep front wave, much less than stated possible by some engineers.

If it is assumed that 40 per cent of the surge appears between the first 2 coils, we can estimate the actual voltages between these coils with the coordinating gap or the arrester. The maximum full positive 1½-40 wave for the 34.5-kv class, if the coordinating gap alone were used, is approximately 175 kv, and 70 kv might appear across the first duct. A modern design of arrester would lower the terminal voltage to about 125 kv which would result in 50 kv across the first duct. If we assume the use of a surge absorber, it would have to slope a full wave, enough to reduce the voltage across the first duct from 70 to 50 kv to be equivalent in protection value with the arrester. To obtain this protection, a sloping of the wave front of from 8 to 12 microseconds by the surge absorber would be required. It still would retain the disadvantages of permitting outages with all waves higher than the maximum full wave value at the coordinating gap.

The next case to be considered is the core type transformer, which has an initial voltage distribution as shown in Fig. 4. Tests upon a similar transformer, 34.5 kv, 25 kva, with 12 pancake coils, each of 400 to 800 turns, showed results as shown in Table 1.

TABLE I

| Surge front | Wave tail | Voltage from line to ground | Max. voltage across 1st duct | Max. voltage across 2nd duct | Max. voltage across 3rd duct |
|---|---|---|---|---|---|
| (Microseconds) | | | | | |
| ½ | 45 | 100% | 77% | 50% | 43% |
| 3 | 32 | 100% | 71% | 50% | 42% |
| 11 | 50 | | 56% | 55% | |

Translating this data from percentages of terminal voltage across the first duct into actual voltages across the first duct, we would obtain 77 per cent of 175 kv, or 135 kv using the coordinating gap alone, 95 kv with an arrester, and 98 kv if we used an absorber sloping the wave front 11 microseconds, about the same degree of sloping as required by the shell type design.

From the data available, the maximum sloping to be expected from surge absorbers available probably is from 2 to 4 microseconds. It is apparent, therefore, that such surge absorbers cannot furnish protection to the transformer coil-to-coil insulation as compared to the modern arrester.

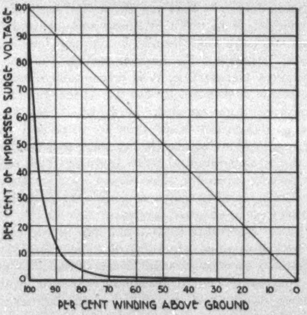


FIG. 4—REPRESENTATIVE INITIAL VOLTAGE DISTRIBUTION OF CORE TYPE TRANSFORMER OF SMALL SIZE

Further, such absorbers cannot reduce the magnitude of long waves. For the cases just described, the lightning arrester will reduce the surge to approximately 125 kv against the 175 kv permitted by the coordinating gap.

To sum up the relative merits of the various protective means, the following comments may be made:

1. In the case of the surge proof transformer, sloping the front is unnecessary as the major, coil-to-coil and turn-to-turn insulations are all coordinated to the coordinating gap level on the basis of steep-front, long-tail surges. Lightning arresters provide a desirable increase in the factor of safety and freedom from outage.

2. In the case of older transformers, it can be seen that winding protection to a far higher degree than seems economical with surge absorbers is obtained with modern lightning arresters properly applied. The further advantage of freedom from outage is obtained with the arrester. Further experience shows that any transformers in service need protection of the major insulation, such as the insulation from the leads to the tank, etc., as much or more than protection of the windings. In this case, it is futile merely to slope off the front of the surge a few microseconds.

3. It should not be overlooked that a surge absorber, with inductance and capacity built in, is in fact another piece of equipment similar to the transformer, and with exactly similar problems. It requires bushings, windings, insulation and case. It bears a close resemblance to the line coils and insulation of the ordinary transformer, and it seems unnecessary to solve this question in both places without compensating advantages.

**Philip Sporn:** Satisfactory lightning protection of transformers requires three principles to be kept in mind: First, the transformer must physically be protected so that failure within the transformer does not occur, as such failure is expensive to repair and may involve a prolonged outage to service. Second, this protection must be supplied without permitting even a momentary outage to service, that is, without circuit interruption. Third, and this is altogether too frequently forgotten, protection must be obtained on an economical basis. Lightning protection obviously is another form of insurance, either insurance of service or insurance of equipment, or both, and there is a limit to the amount that can be spent on any form of insurance.

The coordinating gap would appear to offer a fairly satisfactory solution, coming within the above specifications on transformers of new design, and particularly on shielded transformers. On transformers of the older design, it appears that the coordinating gap would have to be set so low that while protection would be offered to the transformer, the resulting service outages might become so great that the entire scheme ceases to be practical.

The authors point out that one of the best methods of transformer protection is to use a lightning arrester, and have suggested that the wave modifier also be employed with the lightning arrester. Since a wave modifier reduces the coil and turn stresses inside a transformer, it is reasonable to suppose that added protection is supplied by the use of the wave modifier in addition to a lightning arrester. However, it may prove more economical to design the transformer to withstand these turn and coil stresses and merely use the lightning arrester, rather than go to the use of an additional wave modifier which of necessity must be relatively expensive, since regardless of its large size and internal makeup, it will employ one or more expensive bushings of a rating equal to or in excess of the transformer itself.

The authors' statement that a rod gap (coordinating gap) should be looked upon as a last line of defense for transformers and stations and used irrespective of the presence of protective means, is in line with a doubt heretofore expressed by the writer and by many others as to the ability of the lightning arrester properly to perform its function under all conditions. It has been recognized in the past that a lightning arrester if it could only function according to its theoretical indications would be a most effective protective device. However, operating experience very seldom has backed up these theoretical indications; in fact, as has been previously pointed out by the writer, in many places transformers have failed although protected by lightning arresters installed in the most approved manner. Further, as again has previously been shown, only one actual field record, and that of 2,620 amperes associated with 700 kv close to the arrester, has ever been obtained, to the writer's knowledge, definitely indicating high ampere discharge by a lightning arrester during a time of excessive voltage rise at the lightning arrester apparatus terminal, this in spite of the fact that from every theoretical consideration such a condition must exist when a lightning arrester functions and performs properly.

It is possible that some of the difficulties experienced heretofore with lightning arresters have been due to operating engineers following altogether too closely the practice recommended by the lightning arrester engineers. The latter, as would naturally be expected, have always had a tendency to lean in the direction of a cell or unit arrangement that would give protection to the arrester under all conditions, but it is obvious that an arrester that is not exposed to lightning punishment, so to speak, may have a very difficult job of justifying its existence, and that if one has to choose between having an arrester that would be in itself safe under all conditions although doing very little protective work, and an arrester installation that would do a very effective protective job but in that process would expose and subject itself to the possibilities of even failure—then, between these two, there is no other choice except to expose the arrester and take the consequences.

In an effort to improve the grade of protection furnished to the equipment by lightning arresters on the various systems with which the writer is connected, there have been changed during the past few years a very large number of 132-kv arresters so as to limit lightning voltage to the lowest possible value consistent with reasonable safety. In doing this we appreciated that we were increasing the duty on the arrester and of course the possibility of its failing in service, but we have definitely made up our mind that the best way of determining the limit of the arrester is to try it out in practice under conditions that will allow it to provide maximum protection to the apparatus which it was designed to protect and less protection to itself, until we find a point where arrester failure is a problem in itself. In other words, we have definitely taken the arrester out of the decorative class and have put it to work.

The practical limits of the application of the wave modifier have been thoroughly discussed by the authors; it must be evident from their analysis that wave modifiers alone in their present form offer only partial protection to transformers against lightning entering the station, even if their size and cost can be kept within practical limits. Another serious drawback to the wave modifier according to the authors is the change in design required for protection to different types of transformers and lines. It is not clear, however, how much of a drawback this would be and whether it would be necessary to change these wave modifiers in a given station as additional equipment may be added to or removed from the station. The lightning arrester on the other hand does not have this limitation.

The general conclusion that one must draw from the authors' paper is that an ideal protective system would consist of a coordinating gap, lightning arrester, and wave modifier; but the weakness of this conclusion is that it prescribes too much and that in general this complete prescription cannot be afforded What is needed is a universal protective device, easily applied and cheap enough to justify itself even where the economic conditions are rather thin. The use of the elaborate system proposed by the authors can very rarely be justified in practice.

**K. K. Palueff:** Messrs. Norris and Thomson limited their contributions to the discussion of the wave modifier which their company manufacturers. We shall therefore attempt to evaluate the action of their device in the light of general data on wave modifiers presented in our paper and the data published by Messrs. Norris and Thomson.

In our discussion of the action of the absorber we also should bear in mind that Mr. J. M. Thomson agrees that his absorber (for a 22-kv system) would act as shown in Fig. 11 of the paper. By necessity it follows that a device that behaves as shown in Fig. 11 also will behave as shown in Figs. 12, 13, 14 and 15, since they all are records of test on one and the same device. The data of these figures therefore are used as a part of our arguments.

*Term "Surge Absorber."* Messrs. Norris and Thomson now agree with us that the term "absorber" used for their device is not justified from the standpoint of energy absorption. The term "surge absorber" when referred to by these discussors covers their protective device irrespective of its rated voltage. From studying various technical papers presented by Messrs. Thomson and Norris and our own experimental work with this type of device, we found that from the electrical standpoint the low voltage surge absorbers differ radically from the high voltage absorbers. For example, tests show that the effect of a 2,300-volt absorber is essentially that of an inductance. This is proved by the fact that whether the case of the absorber is grounded or isolated, the modification of the incoming surge by the absorber is practically the same. In a 22-kv absorber, on the other hand, both the inductance and the capacitance to ground are important. The proof is that disconnecting the case of the absorber from ground radically changes the modification of the incoming surge by the absorber.

Thus while the value of ground resistance of the ground connection of the low voltage absorber has no effect upon its behavior, the value of the ground resistance for the high voltage absorber has a very important effect, causing an abrupt voltage rise at transformer terminal. This voltage rise is proportional to

$\frac{R_g}{R_g + Z}$ where $R_g$ is ground resistance and $Z$ is the surge impedance of the line. Mr. E. T. Norris on the other hand in some of his recent papers stated that high ground resistance up to 1,000 ohms has no effect on absorber operation. ("Install Ferranti Surge Absorber and Smile"—*Bulletin 701* by Ferranti Electric Ltd.)

The discussion here is limited to high voltage absorbers only, since the discussions by Messrs. Roper and McEachron treat the low voltage absorber.

*Can Absorber Resonate?* Mr. E. T. Norris in his present discussion emphasizes the importance of the internal absorber losses on its functioning, he states "the disadvantages (possibility of resonance) are obviated by making the combination (of inductance and capacitance of an absorber) aperiodic through the inclusion of a large loss or resistance component." Mr. Thomson also expresses the same opinion in his paper on the subject (*World Power*, May 1932, page 325) where he states "the absorber is essentially a pi section filter with a high resistance element to eliminate the possibility of the inductance of the coil and the capacitance of the transformer resonating and causing doubling of the voltage at the terminal of the transformer."

Neither of the discussors mentions the important "damping" effect of the surge impedance of the connected line which acts in the case of a single impulse as a resistance equal to the surge impedance of a line and connected in series with the absorber.

It is our conviction, supported by theoretical and experimental evidence, that an absorber's internal losses are too small to make it aperiodic. Consequently, where an absorber appears in test to be aperiodic it is not due to its internal loss but due to the effect of the external circuit, like for example, that of the surge impedance of connected transmission line. Comparison of the test curves Nos. 1 and 4 of Fig. 11 of our paper, as well as that of calculated curves of Fig. 5 of this discussion demonstrate this.

The calculations of Fig. 5 were made with formulas of our own derivation which numerically agree with those published by Mr. Thomson in the above mentioned paper. The constants used for the calculation are taken from the test results on a 22-kv absorber, made by Mr. Krug of Germany and by other experimenters. It was found that the absorber constant varied with the value of electrostatic capacitance of the transformer connected. Curve 5 shows that if dependence could be placed on the surge impedance of the line, then much better results would be secured with a plain capacitor having the same electrostatic capacitance as the absorber, and omitting entirely the inductive element which, as curve 2 shows, is a detrimental feature of an absorber.

In case the resistance of the absorber is 100 ohms, which is the maximum assumed by Mr. J. M. Thomson in his paper, then the crest value of curve 2 will rise to 149 per cent rather than 170 per cent as in the case of 50 ohms, but the general relation of the curves will not essentially be modified.

Comparison of test curves 1 and 2 of Fig. 15 of the paper demonstrates the fact that connection of the absorber in the circuit may appreciably increase the internal stresses in a transformer due to resonance of the absorber circuit with the transmission line, in case the latter is arced over at some distance from the station. Mr. Thomson's statement ". . . absorber does not introduce resonance under any normal condition of operation," therefore, is not correct, since arcover of the line insulation during lightning storms must be considered as one of the most "normal" conditions, meaning by the word "normal"—common.

An arcover of the line insulation near the terminal of the absorber and arcover of a transformer bushing are two more cases of normal operating conditions where the absorber can not depend on damping effect of surge impedance of the line, since after the arcover takes place the line obviously can not have any effect on the phenomena within transformer windings. Yet under these conditions extremely high internal stresses are created in transformers. Oscillograms of Fig. 6 of this discussion are extremely illuminating in this respect. Curve 3 of Fig. 13 of the paper shows that a steep wave produced, in transformer of short natural period, a voltage some 14 times the ideal. That is, 42 per cent of the voltage applied to the transformer was concentrated across 3 per cent of the winding near the line end. By connecting a "protective transformer" between line and power transformer, the voltage produced by the same wave was reduced to 5.7 times the ideal. This might have been taken as evidence of the effectiveness of the protective transformer. Yet

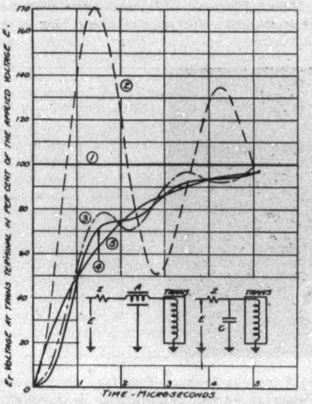


FIG. 5—EFFECT OF SURGE IMPEDANCE OF TRANSMISSION LINE AND OF INTERNAL MODIFIER LOSSES ON MODIFIER OSCILLATIONS

Curve 1—Applied voltage $E$

Curves 2, 3, 4 and 5—Resultant voltages at trans. terminal (calculated)

Curves 2, 3, and 4—Obtained with trans. protected by absorber

Curve 5—Obtained with trans. protected by shunt capacitor of 0.0034 microfarads

ABSORBER CONSTANTS USED FOR CALCULATION

| | Resistance | Capacitance | Inductance | $Z$ |
|---|---|---|---|---|
| Curve 2 | 50 ohms | $3400 \times 10^{-12} F$ | $100 \times 10^{-6} h$ | $O$ |
| Curve 3 | 0 | $3400 \times 10^{-12} F$ | $100 \times 10^{-6} h$ | 400 ohms |
| Curve 4 | 50 | $3400 \times 10^{-12} F$ | $100 \times 10^{-6} h$ | 400 ohms |

when the line insulation near the protective transformer was permitted to arc over, the voltage across the same part of the winding first rose to 5.7 times normal as before, due to the front of the applied wave, and then fell below zero line to 14 times normal, due to the abrupt tail of the applied wave. This confirms our view that arcover of the line at the absorber terminal can produce just as high stresses with as without a protective device of absorber characteristics, and that such a device is incapable of reducing the stresses under such conditions.

Since Messrs. Norris and Thomson agree with us that the absorber does not reduce the amplitude of a surge, it follows that should the surge be high enough to arc over the transformer bushing where no absorber is installed, it would also arc it over in the case the absorber is installed. This would permit the most abrupt fall in voltage from the maximum amplitude that can possibly be applied to the transformer and therefore would create exceedingly high stresses due to resulting internal oscillations of the transformer. The presence of the absorber frequently will accentuate these oscillations as shown in our paper.

Since Messrs. Thomson and Norris agree that the absorber can have no material effect on a relatively long wave they, by necessity, must agree that it is incapable of reducing stresses in major insulation since the stresses are produced principally by long waves.

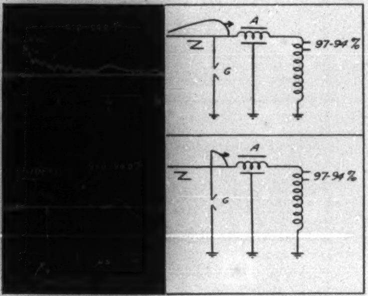


Fig. 6—Increase in Stresses Produced by Arcover at Line Terminal of the "Protective Transformer"

Top—Voltage across 3 per cent of winding near line end (97—94 per cent away from ground end) produced by steep traveling wave (5.7 times ideal)

Bottom—Voltage between same points produced by wave of the same shape and amplitude but allowed to arc over gap G. (14 times ideal)

Thus we are obliged to conclude that, as far as the transformer is concerned, if *all* common or "normal" operating conditions are taken into consideration an absorber is quite impotent in reducing dangerous stresses in turn, coil or major insulation.

Mr. Thomson speaks of some tests made in this country and in Germany, results of which he believes prove that the absorber does not oscillate. It is difficult to comment on this statement as he fails to give any definite reference to the condition of test, the numerical results obtained, and the name of the authors of the tests.

The only results of tests made in Germany that have been published and brought to our attention are those made by Krug of Dresden in Doctor Binder's Laboratory (*E.T.Z.*, June 1932). Probably it is this test that Mr. Thomson has in mind as one of Krug's oscillograms has been widely published by Mr. Norris and his associates on several occasions.

It is significant that this oscillogram was not obtained with a transformer being "protected" by the absorber but was secured with the absorber connected between two parts of a transmission line.

Mr. Krug has this to say about the 22-kv absorber he tested:

"The damping resistance of the absorber is relatively small, therefore the damping has to be effected by the *surge* impedance of the connected overhead lines. *Over voltage can be expected* at the end of long cables (underground), provided the cable does not produce any flattening of the front itself. Tests do not seem to show any great influence of permeability of the iron tank and of the skin effect of the conductors."

By over voltage Mr. Krug means that the absorber may cause increase in the voltage applied to the apparatus in case the surge impedance of external circuit is low, like in a cable. Ability to cause such increase is the fundamental characteristic of a resonating circuit. It will be observed therefore that Krug's findings confirm our views on the resonating characteristic of absorber and that it is not the internal loss but the damping effect of the surge impedance that under some condition may make circuit aperiodic in spite of the presence of absorber. Thus, the writer does not see how Mr. Thomson finds confirmation in his views in the above tests.

*Effect of Absorber on Number of Line Arcovers.* Mr. Norris states that the absorber reduces the number of flashovers and blowing of fuses. This is quite surprising since he agrees that the absorber does not reduce the amplitude of a surge even at its own terminals. If, for the sake of discussion and neglecting evidence to the contrary, we should assume, that, it causes some essential modification in the wave, then still its effects would be limited to the section of the line in the immediate neighborhood of the device. It is general knowledge that relief or discharge or in fact a direct ground on a circuit conductor can not be depended upon to prevent line flashover even one span away. Since the law of probability suggests that most of the lightning flashovers take place over the major part of the transmission line, no appreciable reduction of the total number of flashovers can possibly take place. As the blowing of fuses is due to abnormally high amplitude of the surge, which is not affected by the absorber, followed by power current it also is not clear how the number of blown fuses can be reduced.

*Repeat Orders and Service Experience.* It is difficult to attach any engineering significance to Mr. Norris' statement "no instance has been recorded of failures of surge absorbers to give complete protection within their sphere of action," as long as he does not define the "sphere of action."

Mr. Norris is encouraged by the fact that his company has received many repeat orders for absorbers. As encouraging as it may be to his company, it fails to serve as evidence of the effectiveness of the device. For example, in the past, when a choke coil "was in flower" the manufacturers of choke coils could, with similar satisfaction, point to the large number of repeat orders. Yet, now, the manufacturers of such coils, as well as Mr. Norris, agree with us that these coils offer no protection and can be even harmful. From what we know of the absorber we are inclined to believe that the two cases are quite comparable.

As the number, frequency, amplitude, and shape of transient voltages depend on a great many factors and characteristics of circuits which generally are not known, it is very dangerous to base the design characteristics of protective devices on indiscriminate reports received from the field. Many examples can be cited to illustrate how misleading some of these reports can be.

*Size of Absorbers.* Our conviction is that the physical size of a wave modifier of the absorber type in most cases becomes impractically large where its electrical constants are made of proper magnitude.

Mr. Thomson tells us that the sizes of his absorbers are even larger than we indicate in the paper. Apparently, he misunderstood our data. In Fig. 7 of this discussion, the volume of proper wave modifiers (of the absorber type) are compared with those of his standard absorbers and with typical large power transformers of stated rating.

It must be observed that the volume of the proper wave modifier increases materially with increase of the natural period of free oscillation of the transformer to be protected. The size of the absorber, on the other hand, does not, and still it is much smaller than the smallest of the proper wave modifiers. Comparison is made on the assumption that in the absorber, the wave modifier, and the transformer the same kind of insulating material is used. It can be seen that, in most of the cases, the proper wave modifier is absurdly large. This appears to us as one more evidence that the surge absorber can not be effective, being so much smaller than the wave modifiers.

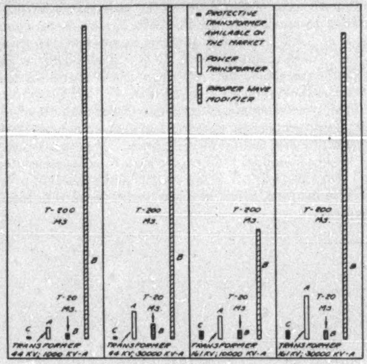


FIG. 7—COMPARISON OF VOLUMES OF:

A—Power transformers of different ratings
B—Corresponding proper wave modifier of "protective modifier" type designed for transformer natural period *T* of 20 and 200 microseconds
C—Wave modifiers of the same type available on the market

*Distributed Capacitance of Oil Immersed Surge Absorber.* We estimated in the paper that the maximum capacitance of a high-voltage oil-immersed protective transformer winding to its case (that is to ground) should be of the order of 0.0004 microfarads if the cost of the device is to be kept within practical limits. Mr. Thomson states that this capacitance in his absorbers is 10 times as high, but admits that in the high-voltage range the absorber can not compete in price with lightning arresters. While we failed to find any test data on high voltage absorbers, published by Thomson or his associates, we must agree that if the cost of the device is to be disregarded, this capacitance can be made even 100 times the value mentioned by us.

Incidentally, in one of the latest publications on the absorber (*Bulletin 701* mentioned previously) issued by Mr. Thomson's associates, the estimated capacitance of the high voltage absorber to ground is given as 0.001 microfarads. This is much nearer to the 0.0004 suggested by us than to the 0.004 suggested by Mr. Thomson. After all, our figure was stated to indicate only "the order of magnitude." But it is rather surprising to find a 4:1 difference in the estimate of this capacitance between various engineers responsible for the absorber.

*Mr. D. W. Roper's Discussion.* Mr. Roper's discussion shows how effective a lightning arrester is where full advantage of its properties is taken. Comparing his present data on transformer failures with that given in his A.I.E.E. paper, TRANSACTIONS, Volume 51, 1932, we find that before interconnection of a transformer secondary neutral wire with the arrester's ground the rate of distribution transformer failures on his system was 0.4 per cent per annum. After the interconnection was completed this rate fell to 0.14 per cent per annum. In other words the effectiveness of the arrester protection was increased 2.85 times by the virtue of improved installation.

It is unfortunate that not many operating engineers exercise as much care and determination as does Mr. Roper in the analysis of the experience of their systems. Much benefit could be derived from their experience, if as in Mr. Roper's case, they present definite facts rather than general impressions and independent interpretations.

*Typical Lightning Waves.* Mr. Norris states that most of the failures of his transformers take place between turns. Since it is known that the maximum stresses between turns are produced by very short steep waves he concludes that only these kind of waves are important and typical to transmission lines.

Mr. F. J. Vogel, on the other hand, states that he has troubles principally with major insulation of his transformers. Since waves producing maximum stresses in major insulation do not have to be particularly steep, but must have considerable length, the conclusion from his experience should be, that it is this type of wave that is most important and typical of transmission lines.

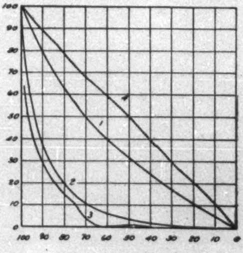
Since both discussors evidently had the experience with a large number of transformers the only conclusion that can be drawn, which does not conflict with their experiences, is that waves of both types are present, but one type of transformer is too weak in its turn insulation and the other in the major insulation. We have expressed on many occasions our conviction that the transformer designer must consider the entire range of waves as probable and therefore design the insulation accordingly.

*Vogel Discussion.* We are glad to learn that Mr. Vogel's analysis of the effect of protective devices supports our view on relative merits of wave modifiers and lightning arresters. However, his curves of initial or electrostatic voltage distribution (Figs. 3 and 4) of shell and core type transformers may be misleading without the following comments:

The striking difference between the 2 curves is not due to the difference in the type of the 2 transformers as one may conclude from the captions, but due to the fact that his core type transformer was of an ordinary construction, where no special effort was made to reduce the voltage concentration near the line end; on the other hand, the shell type transformer evidently was provided with an electrostatic shield (this is a rather recent addition to shell type transformers and under some of the transient voltage conditions may reduce the concentration at the line end). The writer's belief in the correctness of this opinion is based on the fact that curves published by Mr. F. J. Vogel and his associates for shell type transformers prior to the adoption of the shield were essentially like that shown by him for the core type while curves published by them after the shield was incorporated coincide with his curve in Fig. 4. As we have shown before, the electrostatic shield can produce such a differ-

FIG. 8—INITIAL OR ELECTROSTATIC VOLTAGE DISTRIBUTED IN CORE AS SHELL TYPE TRANSFORMERS

1. 40,000-kva 220-kv shell type with electrostatic shield (Putman)
2. 25,000-kva 220-kv shell type without electrostatic shield (Vogel & Hodnette)
3. Large 154-kv core type transformer without electrostatic shield (Palueff)
4. Same transformer as No. 3 but with electrostatic shield (Palueff)



ence in the shell type transformer only in case the entire winding is in one group or a number of groups connected in parallel. The latter construction, however, is effective only for limited applications. A reproduction of earlier curves for shell type transformers secured by Mr. Vogel and his associates (A.I.E.E. TRANSACTIONS, March 1931) is shown in Fig. 8 of this discussion and compared with data on core type transformers obtained by us and published in A.I.E.E. TRANSACTIONS, January 1929.

Mr. Philip Sporn is to be congratulated for initiating a program having for its objective the securing of the very best protection obtainable with the arrester equipment. His decision to reduce gradually the safety factor of the arresters until the limit is reached through actual experience is most welcome, as it certainly is the most positive way of determining this limit. Of course, it is appreciated generally that this limit will vary for various systems.

The writer calls to Mr. Sporn's attention the fact that we do not suggest the use of a wave modifier, but merely state that in case the operating engineer wants to have one, then the most suitable wave modifier is a condenser connected in shunt with an arrester. Both Messrs. Sporn and Norris refer to the service experience for indication of impotency of an arrester to prevent transformer failure. Before any weight to these experiences is given it must be realized that there is a large number of different types of arresters which differ esentially in their protective ability. Second, that numerically, there is a greater number of old arresters and transformers than of the modern type. These old apparatus were not always coordinated properly with one another and their installations were made before the effects of various factors were generally appreciated.

The behavior of some of the modern arresters was calculated mathematically, checked experimentally under laboratory conditions, and checked again under service conditions, as for example, has been done by Messrs. McEachron and Wade (A.I.E.E. TRANS., June 1931, p. 479), who secured very valuable and convincing data from elaborate tests made with the assistance of field installations of lightning generator and cathode ray oscillograph on part of a large high voltage transmission system.

The reliable field installations of devices capable of measuring arrester discharge currents produced by lightning are very few in number and therefore it is not surprising that not many records have been obtained up to the present. However, it is interesting to recall that Mr. P. Sporn himself found discharge currents of 2,620 and 1,260 amperes in some of his arresters; (A.I.E.E. TRANSACTIONS, March 1928). These currents are of the order of magnitude that represents nearly maximum current that can be expected on a 132-kv system.

All in all, we believe that a modern transformer protected by a modern lightning arrester properly installed is the most practical solution of the problem up to the present. If protection against direct strokes is desired the arrester should be supplemented by ground wires installed over the station and extending over the line a short distance, which now can be computed with engineering accuracy.

# Current and Voltage Wave Shape
## of Mercury Arc Rectifiers

BY H. D. BROWN* and J. J. SMITH*
Associate, A.I.E.E. Associate, A.I.E.E.

***Synopsis.**—This paper gives data on the voltage and current wave shape of mercury arc rectifiers on both the d-c and a-c side. The values of the harmonics at light load are considered first and the modifications of the harmonics under load due to impedance then are studied. The results of tests on rectifiers are given and are in reasonable agreement with the theoretical values which, for convenience in use, are plotted in the form of curves. The relation between the harmonics in rectifiers with different transformer connections is shown and consideration also is given to modifications introduced when the a-c voltage contains harmonics or has a phase unbalance. A brief discussion is given of some methods of modifying the harmonic voltages in this type of apparatus.*

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### INTRODUCTION

MERCURY arc rectifiers have current and voltage wave shapes that are inherent in the normal operation of the apparatus. It is the object of this paper to discuss the wave shape on both the a-c and d-c side of rectifiers and to show how to estimate the wave shapes of the voltage and the current on either side under operating conditions when the circuit constants are known. Methods available for modifying the wave shapes of rectifiers are discussed. The first part of the paper deals with the d-c side and the second part deals with the a-c side of the rectifier.

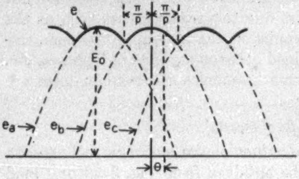

FIG. 1—D-C VOLTAGE WAVE SHAPE OF RECTIFIER AT NO-LOAD

The data given in this paper apply to rectifiers of the customary types that make use of the rectifying properties of a mercury cathode or a thermionic cathode inclosed in an evacuated chamber. They do not apply to rectifying devices in which the normal operation is controlled by a third element generally called the grid.

### PART I—VOLTAGE AND CURRENT WAVE SHAPES ON THE D-C SIDE

The wave shape of the voltage on the d-c side is discussed by considering first the voltage wave which would be obtained in normal operation with balanced polyphase sine voltages applied to the rectifier. The modification due to the presence of unbalances or harmonics in the a-c voltage wave then is considered.

*Theoretical Wave Shape of the D-C Voltage at No-Load*

The voltage on the d-c side at any instant under the no-load condition is the voltage between the cathode and the anode which has the highest positive potential. Thus the d-c voltage wave is made up of the tops of sine waves cut off at intervals $\pi/p$ on either side of the maximum as in Fig. 1, where $p$ is the number of phases. This wave has been analyzed[1] and gives the Fourier series

$$e = E + b_1 \cos p\theta + b_2 \cos 2p\theta + \ldots + b_m \cos mp\theta + \ldots \qquad (1)$$

$E$ is the d-c voltage which is given by the formula

$$E = \frac{E_0 p}{\pi} \sin \frac{\pi}{p}$$

in which $E_0$ is the peak value of the voltage to neutral on the secondary side of the transformer. The coefficient of the $m$th cosine term is

$$b_m = -\frac{2E}{m^2p^2 - 1} \cos m\pi \qquad (2)$$

*Effect of Load Upon the D-C Voltage Wave*

If only one anode at a time is carrying current the voltage wave shape with load is the same as at no load. On account of inductance in the transformer windings and connections the load current cannot be transferred instantly from one anode to another and the currents of two or more anodes overlap during part of the cycle. During the period of overlapping the anodes are at the same potential which is the average of the voltages of the phases with which these anodes are associated. Fig. 2 shows the shape of the d-c voltage wave when overlapping takes place between two anodes. The angle of overlap is designated by the symbol $u$. An analysis of this curve gives the Fourier series

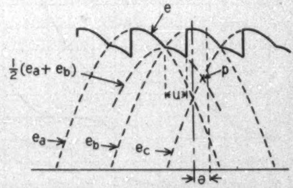

FIG. 2—D-C VOLTAGE WAVE SHAPE OF RECTIFIER UNDER LOAD

$u$ = Angle of overlap

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*General Electric Co., Schenectady, N. Y.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

[1] For references see end of paper.

$$e = E_L + a_1 \sin p\theta + a_2 \sin 2p\theta + \ldots + a_m \sin mp\theta + \ldots$$
$$+ b_1 \cos p\theta + b_2 \cos 2p\theta + \ldots + b_m \cos mp\theta + \ldots \tag{3}$$

In this equation $E_L$ is d-c voltage under load, given by the formula[2]

$$E_L = E \cos^2 \frac{u}{2} \tag{4}$$

$E$ is the d-c voltage at no load. Formula (4) allows for the effect of overlapping but does not allow for the arc drop or the $IR$ drop due to losses in the transformer windings.

The coefficients of the $m$th sine and cosine terms are respectively[3]

$$a_m = \frac{E}{2} \cos m\pi \left[ \frac{\sin (mp+1)\, u}{mp+1} - \frac{\sin (mp-1)\, u}{mp-1} \right] \tag{5}$$

$$b_m = \frac{E}{2} \cos m\pi \left[ \frac{\cos (mp+1)\, u}{mp+1} - \frac{\cos (mp-1)\, u}{mp-1} - \frac{2}{m^2p^2-1} \right] \tag{6}$$

The effective value of the harmonic of order $mp$ is $\sqrt{a_m^2 + b_m^2}$. The harmonics can be referred to the d-c voltage with load by multiplying by the ratio $E_L/E$.

In the 6-phase rectifier the voltage at no-load is cut off at intervals of 1/6 of the period of the a-c supply voltage so that the harmonics which are present on the d-c side are the 6th, 12th, 18th, 24th, etc., harmonics of the supply system frequency. Fig. 3 shows the values of these harmonics as percentages of the d-c voltage with load plotted against the angle of overlap. The curves show the magnitudes only but the phases also change with the angle of overlap.

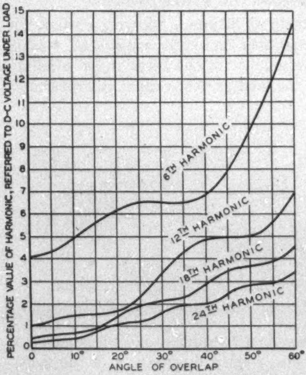

Fig. 3—Harmonics in the D-C Voltage of a Rectifier Plotted as a Function of Angle of Overlap

In the 12-phase rectifier the voltage at no-load is cut off at intervals of 1/12 of a period of the a-c supply voltage so that the 12th, 24th, etc., harmonics of the frequency of the supply system are present. The percentage values of these harmonics at no-load and with load are the same as in the 6-phase rectifier and can be obtained from the curves for these harmonics in Fig. 3. Theoretically the 6th, 18th, etc., harmonics, the odd-multiples of the 6th, are zero for 12-phase operation but actually they exist due to various causes such as the presence of harmonics in the a-c supply voltage, unequal division of load between two sets of 6 phases, etc. The values of these harmonics observed in tests are given later.

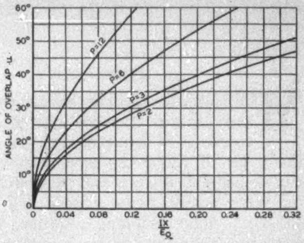

Fig. 4—Angle of Overlap Plotted as a Function of Load

*Calculation of Angle of Overlap*

The percentage values of the harmonic voltages on the d-c side can be obtained from Fig. 3 for any load condition if the angle of overlap is known. The formula for calculating the angle of overlap from the constants of the transformer and the supply circuit has been published.[2] If resistances are neglected the formula is

$$u = \cos^{-1} \left[ 1 - \frac{IX}{E_0 \sin \pi/p} \right] \tag{7}$$

where

$u$ = angle of overlap
$p$ = number of secondary phases in each group*
$I$ = load current in each group of secondary windings
$X$ = reactance from anode to neutral of the circuit in which commutation is taking place
$E_0$ = peak value of voltage to neutral on the secondary side of the transformer

Fig. 4 shows $u$ as a function of $IX/E_0$ for different types of rectifiers. The commutating reactance[4] $X$ is the reactance of the circuit for the current which circu-

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*$p$ also may be defined as

$$p = \frac{360}{(\text{conducting period in degrees}) - (\text{angle of overlap})}$$

The values of $p$ for some of the common connections are

$p$ = 3 for 6-phase double-wye and 12-phase quadruple-wye,
$p$ = 6 for 6-phase star and 12-phase in double 6-phase relation, and
$p$ = 12 for 12-phase star.

lates between the windings undergoing commutation. It includes the reactance in the transformer windings and the reactance in the supply system. The commutating reactance of the transformer can be measured or calculated from the design. The equivalent reactance of the supply system referred to the secondary side depends upon the transformer connection.[4] The following formulas for the equivalent reactance of supply system apply to a number of connections that have been used for 6-phase and 12-phase rectifiers.

(*a*) Secondary double-wye or quadruple-wye, primary either delta or wye

$$X'' = X_s \left( \frac{E''}{E'} \right)^2 \dots \qquad (8)$$

(*b*) Secondary star 6-phase or forked 6-phase, primary delta

$$X'' = \frac{X_s}{3} \left( \frac{E''}{E'} \right)^2 \dots \qquad (9)$$

$X_s$ = line-to-neutral reactance of supply system at fundamental frequency, referred to the primary side of the transformer

$X''$ = equivalent reactance of the supply system at fundamental frequency for the commutating current

$E'$ = voltage to neutral on the primary side

$E''$ = voltage to neutral on the secondary side

The reactance of the circuit in which commutation is taking place is

$$X = X' + X'' \qquad (10)$$

where $X'$ is the commutating reactance of the transformer for the connection used.

### *Effect of Interphase Transformers Upon the D-C Voltage Wave Shape*

The connection known as the double-wye 6-phase connection has two groups of three phases connected by an interphase transformer which causes each group to carry one-half the load current. The voltages on the two sets of phases are displaced by 60 degrees. The voltage on the d-c side is the average of the voltages on the phases that are carrying current. The d-c voltage wave at no load[5] is obtained by plotting the average of two curves similar to Fig. 1 displaced by 60 degrees, each curve being cut off at intervals of 60 degrees on either side of its maximum. It is found by plotting such a curve that it has the same shape as the no-load voltage wave for ordinary 6-phase operation as obtained with the star 6-phase connection. Since the shape of the curve is the same the harmonics of the same frequency are present and their percentage values referred to the d-c voltage are the same.

Under load conditions there is overlapping between anodes in the same group and the d-c voltage wave is obtained by plotting the average of two curves similar to Fig.2 with 60 degrees displacement. It can be shown that for any given angle of overlap the percentage values of the harmonics referred to the d-c voltage are the same as for ordinary 6-phase operation with the same angle of overlap. To calculate the angle of overlap in this case it is necessary to use the commutating reactance between two windings 120 degrees apart since the commutation takes place between anodes placed in such an electrical relation. On the star 6-phase rectifier the commutating reactance between windings 60 degrees apart is taken since commutation takes place between successive anodes. For other 6-phase arrangements such as triple single-phase, 6-phase forked, etc., the percentage values of the harmonics are the same for any given angle of overlap provided the currents of not more than two anodes overlap. In each case the proper commutating reactance for the particular connection must be known in order to calculate the angle of overlap.

In the 12-phase rectifier there also are different arrangements of transformers and interphase transformers which can be used. For instance, one arrangement has two groups of 6 phases displaced by 30 degrees and an interphase transformer which causes the load current to be divided between the 2 groups of 6 phases. It can be shown by analyzing the various arrangements that the 12th, 24th, etc., harmonic voltages are present and their percentage values are the same as in the 6-phase rectifier with the same angle of overlap, provided the currents of not more than two anodes overlap. It is necessary to know the appropriate commutating reactance in each case in order to calculate the angle of overlap for a given load.

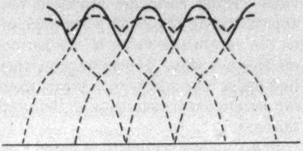


FIG. 5—D-C VOLTAGE WAVE SHAPE OF RECTIFIER FOR A-C VOLTAGE WHICH CONTAINS A 5TH HARMONIC

In formulas (5) and (6) and in the curves of Fig. 3 it is assumed that not more than two anodes in each group are carrying current at the same time. When an interphase transformer is used the number of groups is two or more. For the star 6-phase connection or the 12-phase connection in double 6-phase relation the number of phases in each group is six. When the angle of overlap is approximately 41 degrees (at the point *P* in Fig. 2) a third anode in each group begins to carry current. Thus the curves do not apply above that point. For the double-wye 6-phase connection and the quadruple-wye 12-phase connection the number of phases per group is three. When the angle of overlap is less than 90 degrees not more than two anodes in each group are carrying current and thus the curves which are plotted up to 60 degrees overlap apply over their whole range. For the star 12-phase connection the curves apply up to 20 degrees overlap. The analysis of the voltage curve can be modified to allow for the effect of more than two anodes carrying current but it has not been found necessary to do so because close enough estimates could be made without it and there are other factors such as higher harmonics in the voltage on the a-c side which are not taken into account.

### *Modification of the D-C Voltage Wave Shape Due to Harmonics or Phase Unbalance in the A-C Voltage*

When harmonics are present in the a-c supply voltage of a 6-phase rectifier their effect may be studied by a diagram similar to Fig. 1. In Fig. 5 the heavy dotted lines show the d-c voltage at no load when a sine wave of voltage is applied. The full lines show the conditions that exist when a 5th harmonic in phase with the fundamental is present in the voltage supply. By analyzing the d-c voltage in a Fourier series it is found that the 5th harmonic in the a-c supply gives rise principally to a 6th harmonic and small amounts of 12th, 18th, etc., harmonics. By a similar analysis it is found that a 7th harmonic in the a-c voltage gives rise principally to a 6th harmonic in the d-c voltage. Similarly an 11th or 13th harmonic produces principally a 12th harmonic, a 17th or a 19th harmonic produces principally an 18th harmonic, etc. In all these cases the peak value of the harmonic produced on the d-c side is approximately the same percentage of the d-c voltage as the percentage value of the harmonic producing it on the a-c side. Depending on their phases, these harmonics may add to or subtract from the corresponding harmonics which arise in the normal operation of the rectifier.[6]

In a 12-phase rectifier it is found that an 11th or 13th harmonic on the a-c side gives rise principally to a 12th harmonic on the d-c side, a 23rd or 25th harmonic gives rise to a 24th harmonic, etc.

The action of a 5th or 7th harmonic in the voltage wave shape of a 12-phase rectifier in producing a 6th harmonic on the d-c side requires further study. This may be seen as follows. One method of producing 12 phases in theory is to operate two 6-phase rectifiers in parallel with the primary of one connected wye and the other delta. Let the voltage from line to neutral on the wye be given by

$$e_{\mathrm{AN}} = E_1 \cos \theta + E_5 \cos 5\theta \tag{11}$$

The voltage across the delta will be

$$e_{\mathrm{AB}} = E_1[\cos \theta - \cos(\theta + 120)] + E_5[\cos 5\theta - \cos 5(\theta + 120)]$$

$$= \sqrt{3}\ \{E_1 \cos (\theta - 30) - E_5 \cos 5\,(\theta - 30)\} \tag{12}$$

The factor $\sqrt{3}$ is taken care of by the different transformation ratio for the wye and delta transformer. The negative sign of the 5th harmonic in $e_{\mathrm{AB}}$ shows that it is opposite to the 5th harmonic in $e_{\mathrm{AN}}$ with respect to the fundamental. Therefore the d-c voltage wave during the first 1/12 of a cycle of the fundamental is not the same as during the next 1/12 of a cycle and a 6th harmonic is present. It is found by analyzing the 5th harmonic separately that the percentage value of the peak value of the 6th harmonic so produced is the same approximately as the percentage value of the 5th harmonic in the supply system voltage. The effect of a 7th harmonic can be analyzed in a similar manner and it is found that it produces a 6th harmonic on the d-c side for the same reason.

Other possible sources of harmonics in the d-c voltage of a rectifier are unbalances in the a-c supply due to the angle between the 3-phase voltages not being exactly 120 degrees apart or due to the voltages of the 3 phases not being exactly equal. An analysis shows that the effects to be expected due to these causes on commercial power systems are negligible. The 6th, 12th, 18th and 24th harmonics on the d-c side of a rectifier, when the a-c supply has 1 phase greater than the others by 1 per cent or the angle between 2 of the phases differs from 120 degrees by 1 degree, do not differ by 10 per cent from the harmonics when the magnitudes or the angles between the 3 phases are equal.

### *Comparison of Measured and Calculated Values of the Harmonic Voltages on the D-C Side*

Table I shows a set of readings taken on a 6-phase rectifier which had a d-c reactor in series with the load. The measurements were made across the load. From the harmonic voltage and current measurements the impedance of the load $Z_{\mathrm{L}m}$ at the harmonic frequencies was calculated. The impedance $Z_{\mathrm{R}m}$ of the d-c reactor and of the transformer was estimated from their design constants. From these the internal voltage in the rectifier of the harmonics was calculated for each frequency from the formula

$$e_{\mathrm{R}m} = e_{\mathrm{L}m} \frac{Z_{\mathrm{L}m} + Z_{\mathrm{R}m}}{Z_{\mathrm{L}m}} \tag{13}$$

TABLE I—TEST DATA AND CALCULATED DATA ON A 6-PHASE, 600-KW RECTIFIER

| | | 240-kw load | | | | 720-kw load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Harmonic | Theoretical no-load voltage % | Meas. voltage across d-c load % | Meas. current on d-c side % | Internal voltage on d-c side calc. from measured voltage % | Theoretical voltage on d-c side % | Meas. voltage across d-c load % | Meas. current on d-c side % | Internal voltage on d-c side calc. from measured voltage % | Theoretical voltage on d-c side % |
| 6 | 4.04 | 1.35 | 1.01 | 4.34 | 5.50 | 1.36 | 0.68 | 3.63 | 6.5 |
| 12 | 0.99 | 0.46 | 0.17 | 1.48 | 1.55 | 0.97 | 0.26 | 2.59 | 2.2 |
| 18 | 0.44 | 0.30 | 0.08 | 0.96 | 0.85 | 0.71 | 0.13 | 1.89 | 1.8 |
| 24 | 0.25 | 0.27 | 0.06 | 0.88 | 0.70 | 0.46 | 0.07 | 1.23 | 1.2 |

where

$e_{R_m}$ = internal harmonic voltage of rectifier
$e_{L_m}$ = harmonic voltage measured across load

To calculate the angle of overlap the commutating impedance of the transformer was known from the design. From measurements on the a-c side the impedance of the a-c supply was obtained. Combining these impedances in the manner previously discussed the angle of overlap was calculated from equation (**7**) and found to be 14 degrees for the 240-kw load and 24 degrees for the 720-kw load. Fig. 3 then gave the theoretical percentage values of the harmonics under load. A comparison of these with the values calculated from equation (**13**) shows good agreement except in the case of the 6th harmonic. Measurements for the a-c side showed the presence of 1.9 per cent 5th harmonic and 1.0 per cent 7th harmonic. If these harmonics were in phase opposition to those produced by the normal operation of the rectifier the resultant to be expected on the d-c side would be $6.5 - (1.9 + 1.0) = 3.6$, which now agrees with that obtained by equation (**13**) from the test result. This agreement must be regarded as a coincidence, however, since the phase relations might not have been those assumed.

Table II shows similar tests at different loads on a 12-phase rectifier. It will be noted that there is reasonable agreement between tests and calculated values for the 12th and 24th harmonics. The discrepancies can be accounted for by harmonics present originally in the a-c supply system, and by the reaction of the rectifier on the a-c supply system which produced harmonics in the voltage at the a-c terminals of the rectifier, to be discussed later. These harmonics in turn gave rise to harmonics on the d-c side which were out of phase with and thus tend to reduce those produced by the rectifier under normal operating conditions. The values of theoretical voltage for the 6th and 18th harmonics have been left blank, but it may be noted that they are reduced from what they would be if the rectifier operated 6-phase. The reduction of the 6th harmonic is three to one and in the 18th harmonic is five to one, as compared with a 6-phase rectifier. From a number of tests it has been found that the average reduction in the 6th and 18th harmonics obtained by use of the 12-phase connection approximately is four to one compared with the values which would be obtained if a 6-phase connection were used.

The effects due to harmonics on the a-c side of rectifiers give rise at the present time to the largest sources of error in estimating the harmonic voltages on the d-c side. The difficulty arises principally from the fact that not only have the relative magnitudes of the harmonics to be known but also their phase relations.

### *Method of Reducing the Harmonic Voltages on the D-C Side*

When it is desired to reduce the magnitudes of the harmonic voltages on the d-c side suitable apparatus can be provided. The usual method is to connect a series reactor in the d-c circuit, usually called a d-c reactor, between the rectifier and the outgoing line and resonant shunts across line on the line side of the reactor as in Fig. 6. The resonant shunt consists of an inductance and a capacitance in series tuned for the frequency of the harmonic which it is desired to reduce. A shunt is provided for each harmonic to be reduced. If the resonant shunt is tuned for the frequency of the $n$th harmonic its impedance at that frequency is a pure resistance which is small compared with the impedance of either the reactor or the capacitor at the same frequency. If the resonant shunt is connected as in Fig. 6 and the resistance of the resonant shunt is small compared with the impedance of the load so that the impedance of the load can be neglected, we have

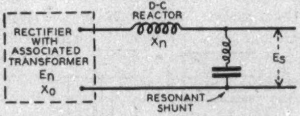


FIG. 6—RECTIFIER WITH D-C REACTOR AND RESONANT SHUNT

$$E_s = E_n r_n / \sqrt{(x_0 + x_n)^2 + r_n^2} \tag{14}$$

where

$E_s$ = $n$th harmonic voltage across the resonant shunt (or outgoing bus)
$E_n$ = $n$th harmonic internal voltage
$x_0$ = internal reactance of the rectifier for the $n$th harmonic
$x_n$ = reactance of the series reactor for the $n$th harmonic
$r_n$ = resistance of resonant shunt at $n$th harmonic

If $r_n$ is small compared with $x_0 + x_n$, the ratio $E_n/E_s$, sometimes called the reduction factor, is approximately

$$a = E_n/E_s = (x_0 + x_n)/r_n \tag{15}$$

TABLE II—TEST DATA AND CALCULATED DATA ON A 12-PHASE, 3,000-KW RECTIFIER

| | | Light load | | Full load | | | |
|---|---|---|---|---|---|---|---|
| Harmonic | Theoretical no-load value % | Measured voltage across d-c load % | Internal voltage calc. from measured voltage % | Measured voltage across d-c load % | Measured current on d-c side % | Internal voltage on d-c side calc. from meas. voltage % | Theoretical voltage on d c side % |
| 6 | | 0.37 | 1.04 | 0.79 | 0.77 | 2.25 | |
| 12 | 0.99 | 0.25 | 0.69 | 0.56 | 0.38 | 1.62 | 1.7 |
| 18 | | 0.038 | 0.108 | 0.047 | 0.02 | 0.13 | |
| 24 | 0.25 | 0.065 | 0.18 | 0.285 | 0.09 | 0.79 | 1.1 |

By properly proportioning $r_n$ and $x_n$ any required reduction in the harmonic can be obtained. The size of the filter depends upon the reduction required, the greater the reduction the larger the filter.

The losses in such an equipment practically entirely are those in the series d-c reactor. The losses in the shunt circuit consisting of inductance and capacitance are negligible. In general the internal reactance $x_0$ of the rectifier is small so that the error in using $x_n$ instead of $x_0 + x_n$ in the above formula is not very great.

## PART II—CURRENT AND VOLTAGE WAVE SHAPES ON THE A-C SIDE

The wave shape of the current in the a-c line which supplies a rectifier is shown first by considering the theoretical wave shape at no-load (light load) and then considering the modification of the wave shape when the rectifier is carrying load. The rectifiers considered are the 6-phase rectifier and the 12-phase rectifier supplied in either case from a 3-phase a-c system through suitable transformers. The current on the a-c side which will be analyzed is the current in the 3-phase line that connects the rectifier transformer to the supply generator or system. The voltage on the a-c side refers to the line-to-line voltage of the supply line at the transformer terminals.

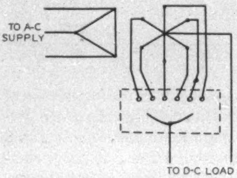


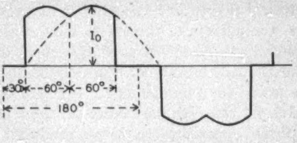
FIG. 7—6-PHASE STAR RECTIFIER

### *Theoretical Wave Shape of the Current at Light Load*

The case of a 6-anode rectifier with transformer connected delta on the primary side and star 6-phase on the secondary side, as in Fig. 7, is considered. The load on the d-c side may be assumed to be a high resistance so that the current is small compared with the normal load current, and the transformer exciting current may be considered as negligible. The rectifier permits current to flow only in the positive direction and the anode which has the highest positive potential carries the current. During the conducting period for this anode the rectifier and its load may be thought of as a simple a-c circuit with resistance. It is assumed that the voltage applied to the rectifier is a sine wave. The conducting period for any one anode is one-sixth of a cycle of the supply voltage. At the end of the conducting period the next anode becomes higher in potential (see Fig. 1) and carries the current. The current then follows the shape of another sine curve displaced 60 degrees from the first. The curve of the current in each line of the supply circuit can be plotted by tracing the current through the complete cycle and the shape is found to be as shown in Fig. 8. This is not a sine-shaped current although the supply voltage was assumed to be a pure sine wave.

It may be noted that the current wave of Fig. 8 approximately is rectangular in shape although the top is rounded slightly since it follows the shape of two sine curves displaced 60 degrees from each other and cut off at intervals of 30 degrees on either side of the maximum. As a first approximation it might be assumed that the current wave is rectangular as in Fig. 9 and has the same average height as the wave of Fig. 8. These waves will be called round-topped and flat-topped to distinguish them from each other.

FIG. 8—NO-LOAD CURRENT WAVE SHAPE FOR 6-PHASE STAR RECTIFIER (ROUND-TOPPED WAVE)

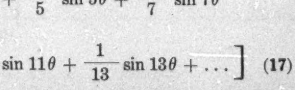


The curves of Figs. 8 and 9 have been analyzed before.[7] The Fourier series for the flat-topped wave in Fig. 9 which may be considered as the theoretical no-load current wave for the star 6-phase connection with delta-connected primary is

$$i = \frac{2\sqrt{3}\,I}{\pi}\left[\sin\theta - \frac{1}{5}\sin 5\theta - \frac{1}{7}\sin 7\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta \ldots\right] \quad \textbf{(16)}$$

Fig. 10 shows the theoretical no-load current wave (flat-topped) for a different 6-phase connection. This is called the double-wye 6-phase connection with delta-connected primary. The two wyes are connected by an interphase transformer that causes the load current to be divided between them. The Fourier series for this curve is

FIG. 9—NO-LOAD CURRENT WAVE SHAPE FOR 6-PHASE STAR RECTIFIER (FLAT TOPPED WAVE)



$$i = \frac{3I}{\pi}\left[\sin\theta + \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta + \ldots\right] \quad \textbf{(17)}$$

It may be noted that the harmonics that are present in either of the 6-phase rectifiers are the 5th, 7th, 11th, 13th, 17th, etc., and may be given by the general formula $6m \pm 1$ where ($m = 1, 2, 3, \ldots$). The magnitude of any given harmonic inversely is proportional to the order of the harmonic for these connections and other 6-phase connections. The phases of the harmonics, however, may be different for different connections as may be seen by comparing the signs of the terms in equations (**16**) and (**17**).

An analysis of the round-topped wave in Fig. 8 gives the Fourier series

$$i = \frac{3.308 I_0}{\pi}[\sin\theta - 0.226\sin 5\theta - 0.113\sin 7\theta + 0.091\sin 11\theta + 0.065\sin 13\theta - 0.0567\sin 17\theta - 0.0454\sin 19\theta + 0.0412\sin 23\theta + 0.0349\sin 25\theta - \ldots] \quad (\mathbf{18})$$

By changing the signs of the coefficients of the 5th, 7th, 17th, 19th harmonics inside the square brackets in (**18**) and appropriately modifying the multiplying factor the Fourier series for the wave in Fig. 10, when modified by rounding the tops of the wave can be obtained. Since the analysis with this type of wave is much more difficult and since in most cases the rectifier operates so that the waves are flat-topped the discussion following is based upon equations (**16**) and (**17**).

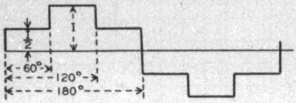


Fig. 10—No-Load Current Wave Shape for Double-Wye 6-Phase Rectifier (Flat-Topped Wave)

Figs. 11 and 12 show current waves for two different 12-phase connections at no-load. The Fourier series for the curve in Fig. 11 is

$$i = \frac{2\sqrt{3}I}{\pi\cos\pi/12}\left[\sin\theta - \frac{1}{11}\sin 11\theta - \frac{1}{13}\sin 13\theta + \frac{1}{23}\sin 23\theta + \frac{1}{25}\sin 25\theta\ldots\right] \quad (\mathbf{19})$$

The Fourier series for the curve of Fig. 12 is

$$i = \frac{4\sqrt{3}I}{\pi}\left[\sin\theta + \frac{1}{11}\sin 11\theta + \frac{1}{13}\sin 13\theta + \frac{1}{23}\sin 23\theta + \frac{1}{25}\sin 25\theta\ldots\right] \quad (\mathbf{20})$$

The harmonics which are present are the 11th, 13th, 23rd, 25th, etc., and may be given by the general formula $12m \pm 1$ where $(m = 1, 2, 3, \ldots)$. The magnitudes of these harmonics inversely are proportional to the order of the harmonic. The Fourier series when the waves are round-topped may be written down by taking the appropriate coefficients from equation (**18**). As in the 6-phase case, the magnitudes of the harmonics are the same for different connections but the phases may be different. While the harmonics of the order $6m \pm 1$ where $(m = 1, 3, 5, \ldots)$ theoretically are zero in the 12-phase rectifier, in actual practise small amounts of these harmonics may be found. These harmonics are discussed later.

*Theoretical Wave Shape of the Current Under Load Conditions*

When the rectifier is carrying load the effect of inductance in the circuit cannot be neglected. On account of inductance the current cannot be transferred instantly from one anode to another and overlapping takes place as stated in Part I. The current waves therefore must be modified to show a gradual building up of the current when the phase becomes active and a gradual falling off when the phase becomes inactive. The calculation of the wave shape would be very complicated if all of the factors, such as resistance and inductance on both sides, exciting currents of transformers, wave shape of the voltage applied to the rectifier, etc., were taken into account. In view of the fact that some of the factors entering into the problem cannot be controlled, for instance the wave shape of the supply system voltage, the lengthy calculations involved would not be justified.

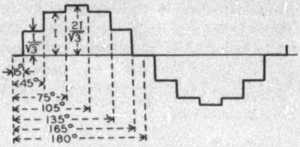


Fig. 11—No-Load Current Wave Shape for Star 12-Phase Rectifier, Primary of Transformer Connected Delta

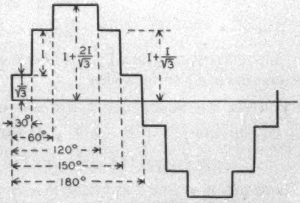


Fig. 12—No-Load Current Wave Shape for 12-Phase Rectifier in Double 6-Phase Relation, Primary of Transformer Connected Delta

As a first approximation the theoretical current waves at no-load (flat-topped) will be modified to allow for the effect of overlapping and other factors will be neglected. The curves so obtained can be analyzed easily. It is shown in the discussion of the test results below that the values of the harmonics obtained from such an analysis correspond approximately to the upper limit of the corresponding harmonics obtained by test.

The curve from Fig. 9 when modified for overlapping has the appearance of the curve shown on Fig. 13. The zero point will be taken as the point where the phase considered begins to carry current; this is 30 degrees to the right of the zero point in Fig. 9. The angle of overlap is represented by $u$. From the analysis upon which formula (7) for the angle of overlap is based[8] the current during the interval from zero to $u$ is given by the formula

$$i = \frac{E_o \sin \pi/p}{X} (1 - \cos \theta)$$

where $\theta$ is the electrical angle and the other symbols are as defined under formula (7). When the load current is transferred to the next phase there is a similar current in the opposite direction so that it subtracts from the load current until the current in the phase is reduced to zero. If it is assumed that the above equation applies, the positive half-cycle of the wave of Fig. 13 can be represented by the following equations that have been written in terms of the load current $I$ and the angle of overlap $u$ from equation (7).

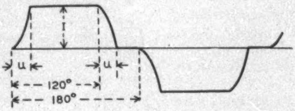


FIG. 13—CURRENT WAVE SHAPE FOR 6-PHASE STAR RECTIFIER UNDER LOAD (FLAT TOPPED WAVE)
$u$ = Angle of overlap

$$i = \frac{I}{1 - \cos u} (1 - \cos \theta) \qquad 0 < \theta < u$$

$$i = I \qquad u < \theta < 2\pi/3$$

$$i = \frac{I}{1 - \cos u} [\cos (\theta - 2\pi/3) - \cos u)]$$

$$(2\pi/3) < \theta < (2\pi/3) + u$$

$$i = o \qquad (2\pi/3) + u < \theta < \pi$$

The current as given by the above equations can be expressed in a Fourier series

$$i = a_1 \sin \theta + a_5 \sin 5\theta + a_7 \sin 7\theta + a_{11} \sin 11\theta + a_{13} \sin 13\theta \ldots + b_1 \cos \theta + b_5 \cos 5\theta + b_7 \cos 7\theta + b_{11} \cos 11\theta + b_{13} \cos 13\theta + \ldots \quad (21)$$

There are no even harmonics in the wave since it is symmetrical. The coefficients $a_m$ and $b_m$ are given by the formulas

$$a_m = \frac{4I}{\pi} \left[ \frac{Q \sin (m\pi/3) - P \cos (m\pi/3)}{m\,(m^2 - 1)\,(1 - \cos u)} \right] \sin\ (m\pi/3)$$

$$b_m = \frac{4I}{\pi} \left[ \frac{P \sin (m\pi/3) + Q \cos (m\pi/3)}{m\,(m^2 - 1)\,(1 - \cos u)} \right] \sin\ (m\pi/3)$$

In these equations

$$P = m \sin u \cos m\,u - \cos u \sin m\,u$$
$$Q = m \sin u \sin m\,u + \cos u \cos m\,u - 1$$

The magnitude of the $m$th harmonic is

$$\sqrt{a_m^2 + b_m^2} = \frac{4I}{\pi}\ \frac{\sqrt{P^2 + Q^2}}{m(m^2 - 1)\ (1 - \cos u)} \sin (m\pi/3) \quad (22)$$

The formulas for $a_m$ and $b_m$ do not apply to the fundamental because the numerator and the denominator of the expressions in the square brackets become zero when $m = 1$. The values of the coefficients for the fundamental are

$$a_1 = \frac{\sqrt{3}\,I}{2\pi} \left[ \frac{\sqrt{3} \sin^2 u + (u - \sin u \cos u)}{1 - \cos u} \right]$$

$$b_1 = \frac{\sqrt{3}\,I}{2\pi} \left[ \frac{\sin^2 u - \sqrt{3}\,(u - \sin u \cos u)}{1 - \cos u} \right]$$

$$\sqrt{a_1^2 + b_1^2} = \frac{\sqrt{3}\ I}{\pi(1 - \cos u)} \sqrt{(u - \sin u \cos u)^2 + \sin^4 u} \quad (23)$$

At the light load the numerator and the denominator of expressions in the square brackets in $a_m$ and $b_m$ approach zero. The indeterminate expressions can be evaluated and the coefficients are found to be the same as in equation (16) provided an allowance is made for the different position of the zero point (see Figs. 9 and 13).

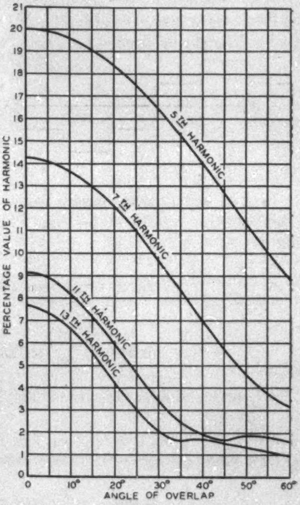


FIG. 14—HARMONICS IN THE LINE CURRENT ON THE A-C SIDE OF A 6-PHASE RECTIFIER OBTAINED BY ANALYZING THE THEORETICAL CURRENT WAVE

Percentage values of the harmonics have been calculated from equations (22) and (23) and are shown in Figs. 14 and 15. It can be shown by analysis that for any given angle of overlap the percentage values of the harmonics are the same for other 6-phase connections if the same assumptions are made as to the shape of the current in each secondary phase.

The current on the a-c side of the 12-phase rectifier can be analyzed in a similar manner. Fig. 16 shows the shape of the load-current curve for the 12-phase connection which reduces to the curve of Fig. 12 at no-load. An analysis shows that for any given value of the angle of overlap the 11th, 13th, 23rd, 25th, etc., harmonics have the same percentage values as in the 6-phase rectifier with the same angle of overlap, and the 5th, 7th, 17th, 19th, etc., harmonics are zero theoretically provided the angle of overlap for the different pairs of secondary windings is the same. The same result is obtained for other 12-phase connections.

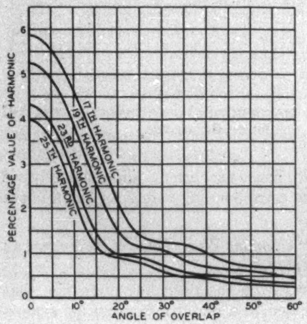


FIG. 15—HARMONICS IN THE LINE CURRENT ON THE A-C SIDE OF A 6-PHASE RECTIFIER OBTAINED BY ANALYZING THE THEORETICAL CURRENT WAVE

The results of this analysis are useful for making preliminary estimates of the values of the harmonics of the current to be expected at any given load when the impedance of the transformer and the supply system are known. The angle of overlap can be calculated by formula (7) and percentage values of the harmonics read from the curves of Figs. 14 and 15 (see discussion of test data below).

### *Test Data on Harmonics in A-C Voltage and Current*

Table III gives the results of tests on the a-c supply of a 6-phase, 500-kw rectifier at approximately full load. The percentage values of current obtained from Figs. 14 and 15 for the calculated overlap are also shown. The discrepancy between the 5th and 7th harmonics obtained from the curves and those actually measured is considerable. For the higher harmonics the agreement is reasonably good. It also may be noted that if the theoretical no-load percentages for the harmonics were taken as applying to the full-load condition the results would be very much in error.

The results of a similar set of tests and calculated values on a 12-phase rectifier are shown in Table IV. There is reasonable agreement between this test and calculated values of the 11th, 13th, 23rd and 25th harmonics at full load. At half load some differences occur. The theoretical values of the 5th, 7th, 17th and 19th harmonics are zero, as pointed out previously. Actually these harmonics are present and at full load their magnitudes approximately are one-fourth of the values for the corresponding harmonics in the 6-phase rectifier in Table III.

TABLE III—TEST AND CALCULATED DATA FOR 6-PHASE, 500-KW RECTIFIER AT APPROXIMATELY FULL LOAD

| Harmonic | Theoretical no-load current % | A-c voltage under load % | A-c current under load % | Theoretical current under load % |
|---|---|---|---|---|
| 5 | 20.0 | 0.73 | 6.5 | 15.2 |
| 7 | 14.3 | 0.37 | 5.2 | 8.3 |
| 11 | 9.1 | 0.59 | 2.8 | 2.5 |
| 13 | 7.7 | 0.36 | 1.85 | 1.6 |
| 17 | 5.9 | 0.37 | 0.82 | 1.2 |
| 19 | 5.26 | 0.26 | 0.65 | 0.85 |
| 23 | 4.34 | 0.16 | 0.30 | 0.6 |
| 25 | 4.00 | 0.13 | 0.43 | 0.5 |

It may be pointed out that although the percentage values of the harmonics in the current wave decrease with load, their actual values in amperes increase with load due to the increase in the fundamental on which the percentage is based.

Test values of the 11th, 13th, 23rd and 25th harmonics in the current on the a-c side for several rectifiers are compared with the calculated values obtained by analyzing the theoretical current wave in Figs. 17 to 20 inclusive. The percentage values of the harmonics are plotted against an arbitrary scale that is proportional either to the load current or the total impedance of the transformers and supply system when the other remains constant. This is based upon formula (7) which shows that changing the impedance has the

TABLE IV—TEST AND CALCULATED DATA FOR 12-PHASE, 1,000-KW RECTIFIER

| Harmonic | Theoretical no-load current % | 50% load A-c voltage % | 50% load A-c current % | 50% load Theoretical current % | 100% load A-c voltage % | 100% load A-c current % | 100% load Theoretical current % |
|---|---|---|---|---|---|---|---|
| 5 | | 0.25 | 3.14 | | 0.41 | 1.34 | |
| 7 | | 0.37 | 1.66 | | 0.35 | 0.56 | |
| 11 | 9.1 | 0.11 | 2.34 | 3.5 | 0.12 | 2.84 | 2.6 |
| 13 | 7.7 | 0.08 | 1.34 | 2.1 | 0.14 | 1.43 | 1.6 |
| 17 | | 0.24 | 0.136 | | 0.23 | 0.23 | |
| 19 | | 0.10 | 0.106 | | 0.05 | 0.17 | |
| 23 | 4.34 | 0.03 | 0.45 | 0.76 | 0.02 | 0.40 | 0.6 |
| 25 | 4.00 | 0.02 | 0.36 | 0.6 | 0.02 | 0.30 | 0.5 |

same effect upon the angle of overlap as changing the load. An angle of overlap of 20 degrees was taken as a convenient reference point and marked 100. The upper scale (which is not a uniform scale) shows the angles of overlap. If the angle of overlap for a particular load is known the point on the lower scale corresponding to that load can be found by referring to the upper scale. Since the lower scale is proportional to the load the point corresponding to any other load then can be found without having to calculate the angle of overlap. It may be noted that the calculated curves correspond approximately to the highest values of the harmonics in the current obtained by test. Many of the test points are somewhat below the calculated curves so that in estimating the harmonics the curves may be taken as an upper limit. It is hoped that further studies will lead to methods for calculating the harmonics more closely for individual cases.

### *Comparison of Current Wave Shapes of 6-Phase and 12-Phase Rectifiers*

In the 12-phase rectifier the 5th, 7th, 17th, 19th, etc., harmonics which should theoretically be zero actually are present in small amounts as noted with reference to Table IV. These harmonics are due to various causes such as the presence of the corresponding harmonics in the a-c supply system, difference in exciting currents of transformers and interphase transformers, or any condition that may give rise to unequal division of load between two groups of 6 phases. Table V shows the average percentage values of harmonics in the a-c supply for several 12-phase rectifiers that have been tested. Average values for 6-phase rectifiers are shown in the table for comparison. It may be noted that the percentage values of the 11th, 13th, 23rd and 25th harmonics practically are the same for either 6- or 12-phase operation. The percentage values of the 5th, 7th, 17th and 19th harmonic currents approximately are one-fourth of the corresponding values for the 6-phase rectifier.

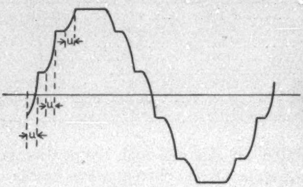


FIG. 16—CURRENT WAVE SHAPE OF 12-PHASE RECTIFIER UNDER LOAD CORRESPONDING TO THE NO-LOAD WAVE SHAPE ON FIG. 12

TABLE V—COMPARISON OF WAVE SHAPES OF THE CURRENT ON THE A-C SIDE OF 6-PHASE RECTIFIERS AND 12-PHASE RECTIFIERS

| | 6-phase rectifier | | 12-phase rectifier | |
|---|---|---|---|---|
| Harmonic | Theoretical no-load value* per cent | Average test value with load per cent | Theoretical no-load value* per cent | Average test value with load per cent |
| 1 | 100.0 | 100.0 | 100.0 | 100.0 |
| 5 | 20.0 | 10.0 | 0.0 | 2.4 |
| 7 | 14.3 | 6.0 | 0.0 | 1.2 |
| 11 | 9.1 | 3.7 | 9.1 | 3.5 |
| 13 | 7.7 | 2.6 | 7.7 | 2.6 |
| 17 | 5.9 | 1.4 | 0.00 | 0.5 |
| 19 | 5.26 | 1.0 | 0.00 | 0.4 |
| 23 | 4.34 | 0.7 | 4.34 | 0.6 |
| 25 | 4.00 | 0.6 | 4.00 | 0.5 |

*These values apply to flat-topped waves (see discussion of *Theoretical Wave Shape of the Current at Light Load*).

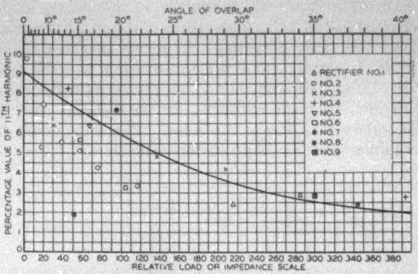


FIG. 17—11TH HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

### *Effect of Rectifier Upon the Wave Shape of the Voltage on the A-C Supply Line*

It has been shown in the preceding discussion that the current supplied to a rectifier from an a-c system contains higher harmonics. These harmonic currents flowing in the impedance of the supply system produce harmonic voltages which distort the voltage on the line supplying the rectifier. When the rectifier is supplied from a power system of large capacity compared with the rectifier and the impedance of the connecting circuit is low the distortion of the a-c voltage is small. When the rectifier is supplied from a system that has a fairly high impedance the voltage on the a-c supply line is

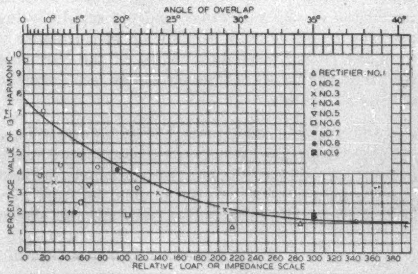


FIG. 18—13TH HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

distorted even though the no-load voltage of the supply generator is a fairly good sine wave. From a knowledge of the harmonic currents obtained from the curves and the impedance of the system the magnitudes of the harmonic voltages can be estimated for 6-phase or 12-phase operation for any given case. In using the curves in Figs. 17 to 20 for making these estimates the impedance of the system at the harmonic frequency under consideration should be used.

The tests in Tables III and IV show an example of rectifiers operated on low-impedance systems. The harmonic voltages on the a-c side with the rectifier operating at normal load are comparable in magnitude with those normally present in the system, showing that the distortion due to the rectifier was small.

The test in Table VI shows an example of a 12-phase rectifier operated on a generator which had a high impedance. In that test the harmonic voltages on the a-c side with normal load on the rectifier (except the 5th harmonic) were large compared with the harmonic voltages in the wave shape of the generator at no-load. It may be noted that the 11th, 13th, 23rd and 25th harmonics are larger than the others as would be expected with 12-phase operation.

### *Methods of Modifying the Current and Voltage Wave Shapes on the A-C Side*

The wave shape of the current supplied to a 6-phase rectifier or a 12-phase rectifier from the a-c supply system can be modified by adding apparatus on the a-c side. One scheme is to provide a local circuit in which the higher harmonic currents that are required by the rectifier in its normal operation can flow. Reactance then may be added in the supply lines to prevent the higher harmonic currents from flowing in the supply system, but the reactance used must not exceed the amount that is permissible for normal operation of the rectifier. The apparatus generally is called a filter.

TABLE VI—TEST DATA ON 12-PHASE, 1,000-KW RECTIFIER SUPPLIED FROM 2,000-KW ALTERNATOR

| Harmonic | A-c voltage rectifier not operating % | A-c voltage full-load on rectifier % | A-c current full load on rectifier % |
|---|---|---|---|
| 5 | 2.48 | 1.52 | 0.72 |
| 7 | 0.79 | 2.05 | 0.27 |
| 11 | 0.18 | 10.75 | 1.07 |
| 13 | 0.10 | 7.02 | 0.39 |
| 17 | 0.07 | 0.99 | 0.03 |
| 19 | 0.06 | 0.54 | 0.04 |
| 23 | 0.02 | 3.19 | 0.10 |
| 25 | 0.02 | 2.39 | 0.05 |

The shunt element may correspond to the resonant shunts that are used for modifying the wave shape on the d-c side, discussed previously. There are other types of shunt elements that can be used, depending upon the frequencies of the harmonics that are to be reduced and the reduction desired. The calculation of the reduction in the harmonics in the current for any given arrangement can be made along the lines briefly discussed in connection with the d-c voltage although the computations generally are more complicated.

When the rectifier is supplied from a 3-phase power system the filter must be 3-phase so that 3 series reactors and 3 shunt elements are necessary. The previous discussion also shows that for each harmonic on the d-c side there are 2 corresponding harmonics on the a-c side—for instance, the 5th and 7th on the a-c side correspond to the 6th on the d-c side. Thus if the resonant shunt type of filter is used, for each shunt on the d-c side a total of six is required on the a-c side. This makes the apparatus for modifying the a-c wave shape more expensive and more bulky than that required for a given modification on the d-c side.

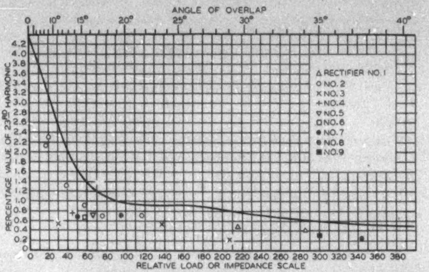


FIG. 19—23RD HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

Another method of modifying the wave shape in theory would be to use an increased number of phases. At the present time it has not been found practicable to use more than 12 phases, and it hardly seems desirable to attempt to increase this number until the causes of the presence of harmonics which should be eliminated by such a connection can be controlled more thoroughly.

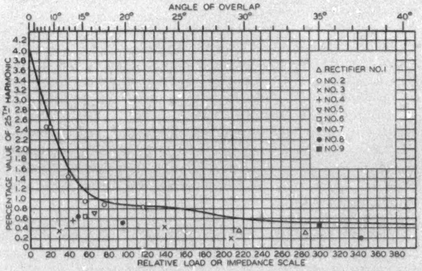


FIG. 20—25TH HARMONIC IN THE LINE CURRENT ON THE A-C SIDE OF RECTIFIERS

The authors desire to acknowledge the assistance of Mr. C. W. Frick in the preparation of this paper.

## References

In the references which follow, the book "Principles of Mercury Arc Rectifiers and Their Circuits," by D. C. Prince and F. B. Vogdes is referred to as Prince and Vogdes, and the book, "Mercury Arc Power Rectifiers," by O. K. Marti and H. Winograd as Marti and Winograd.

1. Prince and Vogdes, p. 91. Marti and Winograd, pp. 88-91.

2. Prince and Vogdes, p. 112. Marti and Winograd, p. 57 and p. 60.

3. Marti and Winograd, pp. 90-91.

4. Prince and Vogdes, pp. 112-114. Marti and Winograd, p. 54 and pp. 113-116.

*Losses in Transformers for Use With Mercury Arc Rectifiers*, E. V. DeBlieux, A.I.E.E. TRANS., Vol. 50, September 1931, p. 999.

"Current and Voltage Conditions Obtaining with the High-Capacity Rectifier," Daellenbach and Gerecke, *Archiv f. Elektrotech.*, January 15, 1925, p. 171.

The formulas (8) and (9) for combining system reactance with transformer reactance are taken from the last paper.

5. Prince and Vogdes, p. 102.

6. "Ripple Voltage of Rectifiers," N. Geise and W. Plathner, *Electrician* (London), December 2, 1932, Vol. 109, p. 714.

7. "Harmonics in the Primary Currents of Rectifiers," Heinrich Jungmichl, *ETZ*, February 5, 1931, p. 171.

8. Prince and Vogdes, pp. 110-112. Marti and Winograd, pp. 55-57.

## Discussion

**P. W. Blye:** The wave shape distortion in the alternating-current and direct-current systems associated with a mercury arc power rectifier, discussed in the paper by Messrs. Brown and Smith, presents interesting problems from the standpoint of inductive coordination with exposed telephone circuits. The increasing use of the rectifier in connection with d-c railway systems and its further application in high-powered radio broadcasting stations have made these problems of increasing importance to the telephone companies.

Several of the earlier rectifier installations on street railway systems resulted in severe noise interference on telephone circuits exposed to the d-c trolley and feeder systems involved. This interference was due to the even harmonics in the rectifier output circuit described in the Brown-Smith paper. As a result of the joint efforts of the electrical manufacturers and the telephone companies, filters were developed which have proved effective as a means of suppressing these disturbing harmonic components and permitting satisfactory coordination with exposed telephone circuits. These filters are now quite generally used where interference from the d-c circuits occurs.

In general, the problem involving wave shape distortion in the a-c supply circuit to a rectifier appears to be more difficult. Except in the case of the smaller rectifiers the use of filters has not, up to the present time, been found practicable due chiefly to the larger number of harmonics present and the greater magnitudes of these harmonics as compared to those in the d-c output circuit. In one case, however, involving a rectifier of approximately 200 kw associated with a 50-kw broadcasting station, a filter was provided in the 2,300-volt a-c supply circuit consisting of an inductance of approximately 13 mh in each phase wire and a delta-connected bank of shunt capacitors of 15-$\mu f$ each. This filter provided a practicable and successful means of improving wave-shape conditions on the a-c supply circuit.

The importance of the rectifier wave-shape problem has been recognized by the Joint Subcommittee on Development and Research of the N.E.L.A.[1] and the Bell Telephone System and its Project Committee on wave shape has recently presented a Technical Report on the subject. This report presents an empirical method of computing the harmonic voltages and currents to be expected from a rectifier and discusses various other phases of the problem including remedial measures applicable in the power system.

As brought out in the paper by Messrs. Brown and Smith, the voltage wave-shape distortion on the supply circuit is proportional to the product of the harmonic currents resulting from the rectifier operation and the impedance of the supply system at harmonic frequencies as looked at from the rectifier. Where a rectifier is supplied directly from a relatively large source of power the impedance of this source at harmonic frequencies would be expected to be relatively small and the voltage distortion would, therefore, be expected to be unimportant. In this case, however, considerable distortion of the current wave-form would be expected on the feeder supplying the rectifier. Where a rectifier forms an appreciable part of the load on a system or where it is supplied over a fairly long circuit or at a comparatively low voltage, the voltage wave-shape distortion, particularly on the supply feeder, may be considerable. Furthermore, this wave-shape distortion may not be confined to the particular feeder from which the rectifier is supplied, but under certain conditions may extend over a considerable portion of the supply system.

In studying possible effects of a proposed rectifier installation on supply system wave shape, it is, of course, very important that a method be available for estimating the magnitudes of the harmonic voltages and currents to be expected. The method suggested by Messrs. Brown and Smith should prove useful as a means of computing the approximate magnitudes of these harmonics.

It is noted that the method proposed by the authors for estimating harmonic currents makes use of the system impedance at fundamental frequency only. This apparently is based on the assumption that the sum of the transformer and system impedances is a simple inductive reactance and that the impedance at any harmonic frequency is, therefore, directly proportional to that at the fundamental frequency. The writer's experience, based on a number of field cases, indicates that the harmonic impedance, which is a combination of inductive and capacitive reactances, may bear no direct relation to the fundamental frequency impedance. At the important harmonic frequencies the system reactance frequently is capacitive and in several cases series or parallel resonant points have occurred at or near these important frequencies. In such cases, the magnitudes of the important harmonic currents from a rectifier may considerably be modified. For example, at or near points of parallel resonance the harmonic currents are comparatively small. For points of series resonance between the transformer and the system, however, the currents are relatively large approaching the theoretical values obtaining in the ideal case of no supply system reactance. In such cases it would appear that the accuracy of the method proposed by Messrs. Brown and Smith would be considerably poorer than in cases in which the supply system impedance is a simple inductive reactance.

**H. Winograd:** The writer compares equations (2), (5), and (6) in the paper by Messrs. Brown and Smith with the corresponding equations on pages 90 and 91 of the book, "Mercury Arc Power Rectifiers," to which reference is made in the bibliography appended to the paper. The corresponding equations in the book are

$$B_{pn} = -\frac{2E_{do}}{n^2p^2 - 1}$$

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[1] The participation of the electric light and power industry is being continued in this endeavor under the auspices of the Edison Electric Institute.

$$A_{pn} = \frac{E_{do}}{2}\left[\frac{\sin(np+1)u}{np+1} - \frac{\sin(np-1)u}{np-1}\right]$$

$$B_{pn} = \frac{E_{do}}{2}\left[\frac{\cos(np+1)u}{np+1} - \frac{\cos(np-1)u}{np-1}\right] - \frac{E_{do}}{n^2p^2-1}$$

Disregarding the differences in the symbols, equations (2), (5), and (6) in the paper differ from the foregoing equations in that they have an added factor, $\cos m\pi$. The effect of this factor is to multiply the expressions for the odd harmonics by $-1$, and the expressions for the even harmonics by $+1$. It should be pointed out that the equations in the paper and the corresponding equations in the book give identical results. The apparent discrepancy is due to the fact that the equations in the book were derived using the point of intersection of 2 consecutive sine waves as the reference point (see Fig. 37 of the book), while in the paper the maximum point of the sine wave was used as the reference point (see Fig. 2).

The effect of shifting the reference point on the expression for the harmonics can readily be seen from Fig. 1 of this discussion showing several sine waves of harmonics. These sine waves do not represent the actual harmonics in the rectifier voltage wave; they are used merely for illustration. If $O$ is used as the origin, the sine waves are expressed by $a_1 \sin\theta$, $a_2 \sin 2\theta$, $a_3 \sin 3\theta$, $a_4 \sin 4\theta$. If $O'$ is used as the origin, the expressions for the same sine waves are, $-a_1\sin\theta$, $a_2 \sin 2\theta$, $-a_3 \sin 3\theta$, $a_4 \sin 4\theta$. The expressions for the odd harmonics have to be multiplied by $-1$, since the negative half cycle of these harmonics starts at $O'$.

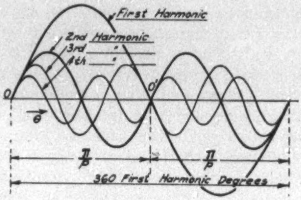

FIG. 1

In discussing the effect of harmonics in the a-c supply voltage on the wave shape of the d-c voltage of the rectifier, the authors have brought out that the presence of a 5th or 7th harmonic in the a-c supply voltage introduces a 6th harmonic into the d-c voltage of a 12-phase rectifier, this is due to the difference of the phase position of these harmonics in relation to the phase voltages of the two 6-phase groups that make up the 12-phase system, and which are displaced from each other by 30 electrical degrees. It should be mentioned here that the presence of these harmonics also may produce unequal d-c voltages from the two 6-phase groups, with the result that one of the 6-phase groups comprising the 12-phase system, and the anodes connected to that group, will take more current than the other 6-phase group. Such current unbalance would produce saturation in the core of the interphase transformer connected between the 2 groups. It would be interesting to know what experience the authors had in connection with this effect of harmonics in the a-c supply voltage on a 12-phase rectifier system.

**H. E. Kent:** Wave shape distortion associated with the operation of mercury arc rectifiers, discussed in the paper by Messrs. Brown and Smith, is of particular interest in the coordination of power and telephone circuits as regards noise induction. The Joint Subcommittee on Development and Research of the N.E.L.A. and Bell System has been working on the general problem of coordination for the past 10 years and recently has devoted considerable attention to the effects of rectifiers. Particular study has been given to the wave-shape distortion on the a-c supply system as recent cases involving noise induction have been more concerned with the a-c side than with the d-c side.

In the problem of noise induction, the power system wave shape is only one of several significant factors. Among other factors of importance are the balance to ground of the power lines, the coupling between the power and telephone circuits, and the type and balance of the telephone circuits. These were discussed in a paper by Messrs. Wills and Blackwell, entitled *Status of Joint Development and Research on Noise Frequency Induction*, presented as Part *II* of the Symposium on Coordination of Power and Telephone Plant at the January 1931 Winter Convention, (A.I.E.E. TRANS., June 1931, p. 448). More detailed quantitative discussions of certain of these factors are contained in various Engineering Reports of the Joint Subcommittee on Development and Research.

A brief description of a recent case of noise induction involving a rectifier may serve to illustrate the bearing of factors other than wave-shape distortion on this problem. In this particular situation, 2 rectifiers, each of 1,000-kw capacity, were installed to supply power to a 600-volt d-c street railway system. No inductive coordination difficulties resulted from the operation of rectifier No. 1. About a year later rectifier No. 2, identical with No. 1, was installed and considerable telephone noise trouble was encountered. Both rectifiers were supplied from the same generating station, of about 100,000-kva capacity, rectifier No. 1 over 3 miles of 13-kv cable, and rectifier No. 2 over 3 miles of 13-kv overhead line. Because of the lower impedance of the cable circuit as compared to that of the overhead line, the voltage wave-shape distortion at rectifier No. 1 was 25 per cent less than that at rectifier No. 2. However, this difference was not sufficient materially to affect the problem.

In neither case were there any telephone circuits exposed to the power circuits between the rectifier and the generating station. The 13-kv circuit feeding rectifier No. 1 also supplied power at that point to several 4-kv distribution circuits serving that portion of the city. This was a closely built up area and all telephone circuits exposed to the power distribution system were in cable.

The 13-kv circuit feeding rectifier No. 2 continued 5 miles beyond the rectifier substation to a distribution substation where the voltage was transformed to 11 kv to serve a fairly extensive 3-phase 4-wire system in a suburban area. The wave-shape distortion resulting from the operation of the rectifier was transmitted without appreciable change to this distribution system. The nature of the power loads was such that it was feasible to use several fairly long single-phase extensions. A considerable portion of the telephone circuits in this area was in open wire, and tree conditions were such that in a number of cases the power and telephone circuits were in comparatively close proximity. As a result of the combined effect of higher distribution system voltage, power circuit unbalance to ground introduced by single-phase extensions, greater coupling, and greater susceptibility of telephone circuits in open wire, considerable noise induction was experienced in the suburban area while no difficulty was encountered in the city area affected by the operation of rectifier No. 1.

As is implied in the above, wave-shape distortion is not reduced appreciably in transformation from one voltage to another. This is important in another type of problem where a rectifier is supplied from a high voltage transmission line. If the capacity of the rectifier and the system impedance at harmonic frequencies are such that wave-shape distortion is caused, this distortion can be transformed to any lower voltage distribution system supplied from the transmission line. There have been some cases of this character where the wave-shape distortion on the distribution circuits has been considerably more important than that on the transmission circuit feeding the rectifier. This was because the distribution circuits had a greater coupling with the telephone circuits as a result of joint construction, and because they involved a considerably larger amount of exposure with telephone circuits than was the case with the transmission circuit.

The information presented in the paper by Messrs. Brown and Smith should be of assistance in making estimates of the effects of rectifiers on wave shape previous to actual installation. Such advance consideration of possible inductive coordination reactions may be particularly advantageous where there is a choice in the method of feeding the rectifier.

**J. J. Smith:** Messrs. P. W. Blye and H. E. Kent refer to the importance of the study of wave shapes in the coordination of power and communication systems. On account of space the paper was limited to a discussion of the wave shape. The authors have been in contact with a considerable amount of the work which both discussors have done in this type of coordination problem. The formula which they have developed and the methods they have used give good results in the study of such cases. It is hoped that at some future date they will present the results of their work in a paper before the Institute.

With reference to Mr. Blye's point as to the proper impedance to use, we have found that in cases where system impedance is a non-inductive reactance the best results for any particular harmonic are obtained by taking the impedance of the system and transformer at the frequency of that harmonic and reducing it to the fundamental frequency. The equivalent impedance thus obtained should then be used in the curves. This point is not made clear in the paper. It is not based directly upon the analysis of the various waves given, but it has been found that it gave the best approximation in a number of instances.

We have calculated a number of individual cases both by the method given in the paper and by the method developed by the Project Committee of the Bell Telephone System and the Edison Electric Institute. The agreement between the two methods is reasonably good and also gives good approximation to the measurements obtained on actual installations.

Mr. H. Winograd points out the difference between phase angles of the harmonics in the d-c voltage wave given in equations (2), (5), and (6) of the paper and those in the book entitled "Mercury Arc Power Rectifiers" by Marti and Winograd. There does not seem to be unanimity in the literature with reference to the zero point which should be chosen for such rectifier waves. It would materially simplify comparison of analyses by various authors if a preferred reference point could be agreed upon.

The effect of the 5th or 7th harmonic on the 12-phase rectifier introducing a 6th harmonic in the d-c voltage wave shape has been referred to in the paper. It also has been pointed out that due to various causes unbalances may also arise between 6-phase groups. These unbalances have been studied to determine whether their magnitude can be reduced but the authors have not attempted to separate the unbalances which may be due to the effects of harmonics on the a-c voltage from those due to other causes.

# Arc Stability With D-C Welding Generators

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Associate, A.I.E.E. Non-member

### THE STABILITY PROBLEM

THE electric arc is used in welding as a convenient means for heating portions of materials which are to be fused, melting the material used for the fusing process, and transferring this material to the weld. It is essential that the progress of these three functions be continuous. Consequently, the rate of heat production at the two terminals of the arc should not be subject to wide variation. This means that the current, and the voltage drops at the anode and cathode of the arc should remain substantially constant during welding. By "stability" as applied to the welding arc, it is desirable therefore to understand not only that the arc should not become extinguished when subjected to various external influences, but also that its current and anode and cathode drops should reasonably be constant.

The d-c welding generator as designed and constructed to supply welding power for a single operator, makes use of a compound field or its equivalent in order that the terminal voltage can be made to fall with increasing current, but without incurring the losses incidental to the use of series resistance for this purpose. On account of the transient interaction of the two fields however, it has been difficult to build such generators so that the arc to which they supply power is as stable as with a simple generator and resistance. The problem of the design of a suitable welding generator therefore becomes one of achieving arc stability with a compound field which is equal to the stability obtained with the simple generator. To this end studies have been made of the transients peculiar to compounded machines[1], but not with sufficient consideration of the properties of the arc itself. A description of the physical ways in which the arc becomes unstable does, however, lead to a satisfactory criterion for designing and testing welding generators that make possible a suitably stable arc.

### NATURE OF THE WELDING ARC

The potential drop across the arc is divided into three parts: that across the cathode region, that across the positive column, and that across the anode region. At the cathode, primary electrons must be supplied in number sufficient, together with the positive ions also formed in the cathode region, to carry the total current. Two types of cathodes are recognized; the thermionic cathode from which electrons are emitted by virtue of high temperature of the cathode material, and the cold cathode in the region of which a sufficient number of electrons are emitted by virtue of high temperature of the cathode material, and the cold cathode in the region of which a sufficient number of electrons are produced without high cathode temperature. For the welding arc, it is often tacitly assumed[2] that the cathode is thermionic. In the case where bare iron electrodes are used for welding, however, there is good evidence that the cathode is of the cold type. The existence of a non-thermionic cathode in a high current arc has been demonstrated in many cases,[3] so that the possibility of such a cathode for the iron arc must be admitted.

Doane[4] indicates by calculations based on a heat balance at the cathode, that the energy input to the cathode is insufficient to vaporize all the material lost during the welding process. The temperature of the cathode must, therefore, be considerably lower than the boiling point of iron—or lower than 2,450 deg C. At this temperature, the thermionic emission from iron oxide, computed from[5]

$$i = AT^2E^{-V/T}$$

where $A = 1.16 \times 10^{-2}$
and $V = 4.44 \times 10^4$

is 0.0072 $A/\text{cm}^2$, a value much too small to carry observed welding currents. Iron being less active thermionically than its oxide would provide a still smaller current at 2,450 deg.

### MECHANISM OF INSTABILITY

In the case of the thermionic cathode arc, instability resulting from increases in the cathode drop is very unlikely because the time required for appreciable cooling and loss of emissivity of the hot cathode probably is long compared with the duration of transient external disturbing influences. In the case of the cold cathode arc, however, an appreciable momentary increase in the cathode fall of potential, or in general, instability of the cathode which may amount to actual loss of the cathode spot, is certainly conceivable.

On the basis of Langmuir's theory of the cathode of an arc, the electron emission from the cathode is effected by an intense electric field (of the order of $10^6$ volts per cm) in the region near the cathode. This field is set up by a positive ion space charge in this region of very small dimensions and close to the cathode. (For a cathode drop of 10 volts, the depth of space charge is of the order of $10^{-5}$ cm.) Any suitable disturbing influence of time duration comparable with that required for these ions to move, under impressed potential, this short distance to the cathode, will alter this space charge and require a greatly increased cathode drop to re-form it. Work by Attwood, Dow and Krausnick[6] on the reignition of a-c arcs indicates that a cathode spot may be lost in a few microseconds.

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For references see bibliography.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

However, in the d-c circuit in the case of loss of cathode spot and consequent fall of current, a voltage appears across the arc space which in practical circuits will be of considerable magnitude, being larger the more sudden the decrease of current. Theoretical considerations indicate that under these conditions, with a potential applied between two electrodes in an ionized space, an ion current flows, which under certain conditions, will change over into an arc. The probability of such a "backfire" in case of the loss of a cathode spot is quite high, due to the magnitude of the suddenly impressed voltage and the short time allowed for diffusion of ions out of the arc space. Consequently a complete loss of the cathode spot and arc extinction would appear doubtful.

A second possible cause of instability in the arc is the increase of drop across the positive column. The positive column energy loss in an arc in a monatomic gas is due principally to the diffusion of ions to the cooler regions of the discharge, or to walls, with resulting recombination and dissipation of energy equal to that required to ionize. To compensate for these ions lost from the discharge, ionizing processes must be set up, and thus a definite potential gradient appears in the space. This loss of energy is dependent upon the area on the bounding walls of the discharge and may be varied by changing the length or diameter of the discharge, or by introducing cool un-ionized gas into the arc space, which cools the arc and provides centers for recombination of ions. In a molecular gas these same processes occur, but in addition, disassociation as suggested by Alexander,[2] may be of importance. It consists in the loss of energy from the arc core by molecular dissociation and the subsequent diffusion away from the core of the arc of the resulting atoms and their later recombination outside the high temperature region of the arc.

In the positive column, the changes in ion density are, among other factors, due to diffusion which is a relatively slow process, especially when the dimensions are large and the gas pressure high. Thus, unless a very high degree of turbulence of the gas is had so that the arc is broken up into filamentary conductors interspaced by regions of cool un-ionized gas, (a condition not found in the welding arc), the time required for changes in positive column drop will be large. Experimentally, instability resulting from loss of the cathode may be distinguished from positive column disturbances by observing the rate of current decrease using an arc in a proper circuit.

### EXPERIMENTAL OBSERVATIONS

A test circuit was used which consisted of a 25-kw 150-volt d-c generator having a water rheostat and an arc connected in series. A 500 $\mu$f condenser was shunted across the terminals of the generator. Its purpose was to permit a very rapid decrease in arc current without the appearance of an excessive voltage across the arc such as would result if an ordinary inductive circuit were used. With the condenser present, only twice the open circuit generator voltage ever is possible across the arc. Calculation shows that if the current in the arc is stopped suddenly the voltage across it is

$$e = E\left(1 - \frac{1}{R}\sqrt{\frac{L}{C}}\sin Wt\right)$$

where

$E$ = generator voltage
$R$ = load resistance
$L$ = generator inductance
$C$ = series capacitance
$W = 1/\sqrt{LC} = 1{,}400$

An arc about 1 cm long between an iron electrode and an iron plate was ignited by separating its electrodes. The current was 50 amperes and the open circuit potential 100 volts. The arc would go out usually in one or two seconds.

Both the cathode ray oscillograph and magnetic oscillograph were used to record the voltage and current of the arc during extinction. Seventeen tests were made and in no case did the arc current decrease to zero in tens of microseconds as would be expected if the cathode spot vanished and so "backfire" occurred. The results are summarized in Table I. Three tests were made with a tungsten cathode (which is thermionic) and gave exactly similar results. Loss of the cathode spot is very improbable in this case.

TABLE I

| Film No. | Time of current decrease sec x $10^{-3}$ | Method of starting |
|---|---|---|
| 1 | 5.0 | drawing |
| 2 | 6.0 | drawing |
| 3 | 4.0 | drawing |
| 4 | 8.0 | fuse |
| 5 | 7.0 | drawing |
| 6 | 0.8 | fuse |
| 7 | 0.4 | fuse |
| 8 | 2.0 | fuse |
| 9 | 8.0 | fuse |
| 10 | 8.0 | fuse |
| 11 | 2.0 | fuse |
| 12 | 8.0 | fuse |
| 13 | 0.25 | fuse |
| 14 | 4.0 | fuse |
| 15 | 5.0 | fuse |
| 16 | 6.0 | fuse |
| 17 | 0.2 | fuse |

In oscillograms of arc voltage obtained during welding with iron electrodes (Fig. 1), pulsations of high frequency and small magnitude are always observed. In oscillograms obtained with a tungsten cathode these pulsations are absent entirely which suggests that they have their origin at the cathode. This was confirmed by placing a thin copper plate with a hole in it near the cathode and using the plate as a probe. With an iron electrode as cathode the same high frequency pulsations were obtained with an oscillograph element connected between cathode and probe as with another element between cathode and anode, which shows definitely that these pulsations have their origin at the cathode region. They do not, however, appreciably influence the stability of the arc.

When using such a probe several oscillograms were obtained when the arc went out. An absence of any rise in potential between probe and cathode during this time again indicates that the instability is not being caused by loss of the cathode spot.

Thus it appears that the cause of instability in the welding arc is an increase in its potential drop due to an increase in losses from the positive column, or possibly an increased cathode fall of potential which does not however amount to an actual loss of the essential cathode phenomenon. So far as external observations are concerned, instability producing disturbances are indistinguishable from simple lengthening of the arc at an equivalent rate and hence for purposes of mathematical analysis, simple lengthening may be assumed as the disturbing influence.

FIG. 1—TYPICAL OSCILLOGRAM OF WELDING

### STABILITY CRITERIA

A typical welding generator circuit is shown in Fig. 2. In this circuit let $L_F$ be the inductance of the field circuit including the leakage inductance of the generator field, and let $L^1$ be the total inductance of the armature circuit. Then these two equations express the voltage relationship in the two circuits.

$$V = M\frac{di_1}{dt} + M\frac{di}{dt} + L^1\frac{di}{dt} + e_A$$

$$E = Ri_1 + M\frac{di_1}{dt} - M\frac{di}{dt} + L_F\frac{di_1}{dt} \qquad (1)$$

The generated voltage $V$ may be expressed as a constant $k$ times the algebraic sum of the field currents if the machine operates at constant speed, and saturation is neglected.

Thus

$$V = k(i_1 - i) \qquad (2)$$

The voltage $e_A$ across the terminals of the arc is a function of the current through it. The equations (1) are of interest for currents near to the welding currents, that is, only over a small range and the arc voltampere characteristic during steady-state conditions, over this range, is practically a straight line of the form $A - Bi$. The transient arc characteristic differs from this straight line, however. For decreasing currents the difference in arc voltage between the steady state and transient values is a constant times the rate of change of current. This is what is meant by the statement that an arc has "inductance." Therefore for $e_A$ the expression

$$e_A = A - Bi + L_A\frac{di}{dt} \qquad (3)$$

may be used, in which $L_A$ is the arc inductance.

If $L$ is defined as $L^1 + L_A$ then equation (1) becomes

$$ki_1 - ki = -M\frac{di_1}{dt} + M\frac{di}{dt} + L\frac{di}{dt} + A - Bi \qquad (4)$$

$$E = Ri_1 + M\frac{di_1}{dt} - M\frac{di}{dt} + L_F\frac{di_1}{dt}$$

If these equations are solved, the resultant equation in $i$ only is

$$\frac{d^2i}{dt^2} + \left(\frac{kL_F - BL_F - BM + RL + RM}{LL_F + ML + ML_F}\right)\frac{di}{dt} + \left(\frac{kR - BR}{LL_F + ML + ML_F}\right)i = \frac{kE - AR}{(LL_F + ML + ML_F)} \qquad (5)$$

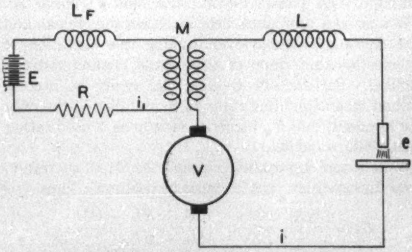

FIG. 2—WELDING GENERATOR CIRCUIT

The steady-state value of $i$, obtained by letting the derivatives of $i$ be zero in (5) is

$$I - \frac{kE - AR}{kR - BR} \qquad (6)$$

The first criterion for stability of the welding arc is obtained from the steady-state condition, and is that $I$ as expressed by (6) must be positive. This is equivalent to stating that the circuit voltampere characteristic and the arc characteristic must intersect at steady state.

Equation (5) may be rewritten in the form

$$\frac{d^2i}{dt^2} + 2\,\alpha\,\frac{di}{dt} + \beta^2 i = \delta \qquad (7)$$

The two roots of this equation are

$$D \;= -\,\alpha \pm \sqrt{\alpha^2 - \beta^2} \qquad (8)$$

or

$$D_1 = -\,\alpha + \omega \text{ where } \omega = \sqrt{\alpha^2 - B^2}$$
$$D_2 = -\,\alpha - \omega$$

if

This condition usually is fulfilled in practise. Consequently the solution of (7) is

$$i = P\epsilon^{(-\alpha+\omega)t} + Q^{(-\alpha-\omega)t} + I \qquad (9)$$

in which $P$ and $Q$ are arbitrary constants.

In order that the arc be stable during transient conditions the terms involving $P$ and $Q$ must vanish after a sufficient time, which means that $(-\,\alpha + \omega)$ and $(-\,\alpha - \omega)$ must both be negative numbers. This will be the case of both $2\alpha$ and $\beta^2$ are positive numbers. Now

$$\beta^2 = \frac{kR - BR}{LL_F + ML + ML_F}$$

For $\beta^2$ to be positive, $k$ must be greater than $B$. This condition, together with the condition that $I$ be positive (equation 6) constitute the stability condition for a simple inductive circuit. These conditions are that the circuit and arc characteristics intersect and that the circuit voltampere characteristic have the greater slope at the point of intersection. Thus in Fig. 3 the arc will be stable when using a simple generator and resistance if its characteristic $A$ lies as shown in relation to the circuit characteristic $C$. It will however, be unstable if $A$ passes beyond the limiting curve $A^1$. When using a compound field machine, the arc can and does become unstable even though this condition of intersection and slope of that static characteristic is fulfilled. Satisfactory welding can easily be accomplished when this limitation as to stability is the only one imposed; that is, if a series resistance is used rather than a compound field.

A new and important criterion for stability results from the condition that $2\alpha$ must be positive. Thus

$$2\alpha = \frac{kL_F - BL_F - BM + RL + RM}{LL_F + ML + ML_F}$$

and $(kL_F + RL + RM)$ must be greater than $(BL_F + BM)$. If the numerator of the expression for $2\alpha$ is equated to zero, then

$$B = \frac{L_F k + MR + RL}{L_F + M} \qquad (10)$$

This equation means that for a generator having given values of the constants on the right hand side the arc will be stable if the $B$ thus calculated is greater than the slope of the arc characteristic, when the latter is determined properly. In other words the generator is good for a $B$ of this calculated value. The question is then, during welding, what is the maximum $B$ of the arc for which the generator must be designed? To answer, the physical cause of instability in the arc must be understood.

It was found in the foregoing that simple lengthening could be taken as the disturbance to the arc causing it to become unstable, since other possible disturbances would act in the same way. Suppose then, that the arc suddenly is lengthened from a normal value to some limiting value. In Fig. 3 for example, let the normal arc of 7 mm length be given by the curve $A$, and the lengthened arc (20 mm) be represented by $A^1$. These arc characteristics are plotted from the equation of an arc between iron electrodes given by Seeliger:[7]

$$V = 15.5 + 2.5l + \frac{9.4 + 15l}{i} \qquad (11)$$

where $l$ = length in mm. The steady-state circuit characteristic in this figure is for a machine having an open circuit voltage of 75 volts. (Saturation neglected.)

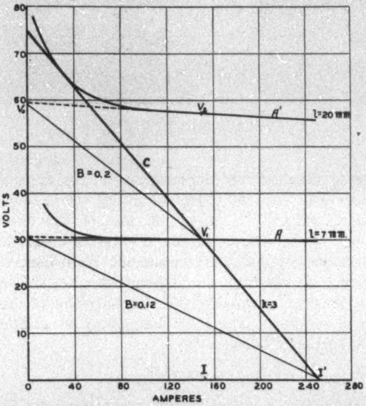

FIG. 3—CIRCUIT AND ARC CHARACTERISTIC CURVES

As a result of this sudden lengthening the voltage across the arc must as suddenly increase from the value $V_1$ to the value $V_2$. The circuit, however, cannot maintain the required voltage $V_2$ at the current $I$, so the current must decrease. The voltage across the arc will not be given by the curve $A^1$, during the current decrease because of the arc inductance, so it follows a curve flatter than the curve $A^1$. Actually the dynamic curve will have a positive slope unless the arc current decreases very slowly. In Fig. 4, a static and dynamic curve are plotted for an iron arc about 10 mm long. The current was caused to decrease in the arc by slowly opening a switch in series. The time for the current to decrease to zero was 0.02 seconds.

As a limit, one may arbitrarily assume that the dynamic curve corresponding to $A^1$ is given by the dotted straight line tangent to $A^1$ at the point corresponding to $I$. The slope $B$ of the arc characteristic will then be at first very large until the voltage becomes $V_2$, and will then be the slope of $A^1$ at the point corresponding to $I$. The average slope from $I$ to zero then is the slope of the line drawn from $I$ on the curve $A$ to $V_0$, which in this case is 0.2. It is convenient to express $B$ as a per cent of the slope of the circuit characteristic $k$. Thus

$$\frac{B}{k} = 66 \text{ per cent}$$

A special case of lengthening of the arc must be considered. During welding, drops bridge from anode to cathode of the arc, completely short-circuiting it. This appears in the oscillogram, Fig. 1. When the drop breaks, the arc voltage suddenly increases to more than its steady-state value, and then falls along a dynamic curve having a positive slope. If, as before, the limit of this dynamic curve is taken as the tangent to the static curve, a straight line may be drawn from the point of intersection of this tangent with the vertical axis to the point $I$, and the slope of this line may be taken as the limiting value of $B$ when the arc is lengthened by the disappearance of a bridging drop. The slope in this case is 0.12, or

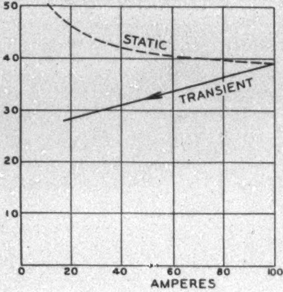

FIG. 4—STATIC AND DYNAMIC ARC CHARACTERISTICS

$$\frac{B}{k} = 40 \text{ per cent.}$$

The slope of the static arc characteristic itself at the point corresponding to $I$ may be taken as the limiting value of $B$ for which a suitable generator must be designed. This would be suitable if the arc lengthened by only a small amount. In the cases cited however, it is conceivable that, although the slope $B$ calculated for the generator is greater than the slope of the arc characteristic is taken in this way, nevertheless the arc might go out. Mathematically, this conception means that, although 2 is positive number, the solution of equation (**5**) might be such that the current necessarily would reverse before reaching its steady-state value. For example in equation (**5**), let $B$ equal zero. Then no inductance $L$ or $L_F$ is needed for stability so far as criteria given so far are concerned. Let all inductance be placed in the field circuit for simplicity. Then $L = 0$, and

$$\frac{d^2i}{dt^2} = \left(\frac{kL_F - RM}{ML_F}\right)\frac{di}{dt} + \frac{kR}{ML_F}i = \frac{kE - AR}{ML_F} \qquad (\mathbf{12})$$

Suppose that the generator is short-circuited by a drop bridging the arc which then breaks away. This gives rise to the terminal conditions that when

$$t = 0,\ i_1 = \frac{E}{R},\ i_2 = I$$

The solution of (**12**) together with these terminal conditions is:

$$i = \frac{A}{k}\left(\frac{kM + kL_F - RM}{kL_F - RM}\right)\epsilon^{-\frac{kt}{M}} + \frac{A}{k}\left(\frac{kM}{RM - kL_F}\right)\epsilon^{-\frac{Rt}{L_F}} + \frac{E}{R} - \frac{A}{k} \qquad (\mathbf{13})$$

In a generator of good efficiency $R$ is much smaller than $k$. If any considerable inductance $L_F$ is found to be required for stability, then $kL_F > RM$. Under this condition the second term of (**13**) will be negative, and also $\frac{k}{M}$ must be larger than $\frac{R}{L_F}$. Thus if the second term is sufficiently large, the current must reverse in going from $\frac{E}{R}$ to $\frac{E}{R} - \frac{A}{k}$. Physically this means that the arc would go out. If the arc is not to go out then in the limiting choice of constants the negative second term must be less than the positive steady-state current. Therefore the condition

$$L_F > \frac{R}{k}\left(\frac{kA}{Ek - RA} + 1\right)M$$

must be satisfied, even if $B = 0$ is the slope of the arc characteristic. This condition holds only when $Ek \quad AR$. Numerically, let the constants of a given generator be

$I$ = 250 amperes
Field voltage = 62.5 volts
Field resistance = 6.25 ohms
$V$ open circuit = 83 volts
$M$ = 0.005 henry
$A$ = 30 volts
Turns ratio field to armature = 25

Then

$$R = \frac{6.25}{25^2} = 0.01 \text{ ohm}$$

$$E = 250 \times 0.01 = 2.5 \text{ volts}$$

$$k = \frac{83}{250} = 0.3$$

It should be noted that in the original equations a turns ratio of one-to-one was assumed, and that the field constants must be expressed in terms of the armature circuit as is customary in transformer calculations. What $L_F$ is now needed for stability even with $B = 0$?

$$L_F = \frac{0.01}{0.3}\left(\frac{0.3 \times 30}{2.5 \times 0.3 - 30 \times 0.01} + 1\right) 0.005 = 0.0037$$

Therefore this value of inductance is required even if $B = 0$ for the arc, because of the rapid initial increase in arc voltage when the arc is formed. It is interesting to see for what average $B$ such an inductance is sufficient. Using equation (**10**) with $L = 0$, and the numerical values previously assumed,

$$B = \frac{0.0037 \times 0.3 + 5 \times 10^{-3} \times 0.01}{0.0037 + 0.005} = 0.125$$

This figure agrees with the value of $B$ determined from Fig. 3 by using the average slope of the dynamic curve for values of current from $I$ to zero, and hence justifies that procedure. It should be noted however that this value of $B$ is higher than required because (1) the arc characteristic actually will bend downward during the transient and (2) the circuit characteristic will bend upward during the transient, whereas both have been assumed to be straight lines. The authors believe however, that the limiting value of $\frac{B}{k}$ of about 60 per cent obtained from Fig. 3 is the best value which can be assigned to this quantity with the limited data at hand, that a generator designed for such a value of $\frac{B}{k}$ using equation (**10**) will be satisfactory for welding, and that this requirement is much less exacting than simply attempting to make the static and dynamic circuit characteristics equivalent.

If in equation (**10**) $L$ is made zero and the equation is solved for $L_F$:

$$L_F\left(\frac{B - R}{k - B}\right) M$$

Conversely if $L_F$ is made zero

$$L\left(\frac{B - R}{R}\right) M$$

Both of these equations show that the stabilizing inductance necessary depends directly on the mutual coupling $M$. With the flexactor[8], the effect is to reduce $M$ considerably, and thus the effectiveness of this device is clearly evident.

### A Test for Welding Generator Stability

If a welding generator is short-circuited, the differential equation involving armature current reduces to

$$\frac{d^2i}{dt^2} + \left(\frac{kL_F + RM + RL}{ML + ML_F + LL_F}\right)\frac{di}{dt}$$

$$+ \left(\frac{kR}{ML + ML_F + LL_F}\right) i = \frac{kE}{ML + ML_F + LL_F} \qquad (\mathbf{14})$$

or

$$\frac{d^2 1}{dt^2} + 2\,\alpha\,\frac{di}{dt} + \beta^2 i = \delta \qquad (\mathbf{15})$$

The terminal conditions are

$$t = 0,\ i_1 = \frac{E}{R},\ i = 0$$

The initial rate of current increase is

$$\left(\frac{di}{dt}\right)_{t=0} = \frac{kE}{R}\ \frac{(M + L_F)}{(ML + ML_F + LL_F)} \qquad (\mathbf{16})$$

Let $T_1$ and $T_2$ be the time constants; that is

$$\frac{1}{T_1} = (-\,\alpha + \omega)\quad \frac{1}{T_2} = (-\,\alpha - \omega)$$

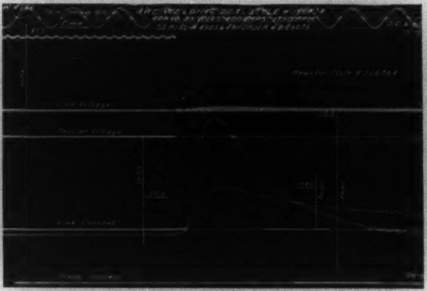

Fig. 5—Oscillogram of Generator Short Circuit

Then

$$\frac{1}{T_1} + \frac{1}{T_2} = \frac{RM + kL_F + RL}{ML + ML_F + LL_F} = 2\alpha \qquad (\mathbf{17})$$

Also

$$\frac{kE}{R} = V$$

Let

$$\left(\frac{di}{dt}\right)_{t=0} \div V = G \text{ and } \frac{1}{T_1} + \frac{1}{T_2} = H$$

Then

$$\frac{H}{G} = \frac{RM + kL_F + RL}{M + L_F} \qquad (\mathbf{18})$$

But this also is the expression for $B$. (Equation **10**.) Therefore to experimentally determine the $B$ for which a generator is sufficient, the following test is sufficient. Short-circuit the generator and with the oscillograph obtain a record of the rise of armature current. From this record measure the initial rate of rise of current in amperes per second and divide this value by the open-circuit voltage. The result then is $G$ in (**18**). From the oscillograph find the inverse sum of the time constants, which is $H$. The quotient then is the value of $B$ to be found. This, divided by $k$, which is the open circuit voltage divided by the short-circuit current should be about 60 per cent or more if the generator is satisfactory during transients.

In Fig. 5 an oscillogram is reproduced showing the results of a test made as described. The initial slope is 80,000. The open circuit voltage is about 100. Hence $G$ is 800.

The current curve is of the form

$$i = C_1E^{\frac{-t}{T}} + C_2E^{\frac{-t}{T_1}} + I$$

To find the time constants, the curve is broken up easily into the three parts shown by the last equation simply by inspection and two points on each logarithmic component is sufficient to find $C$ and $T$. A simpler way to find the reciprocal of the time constant for each of the two component curves, is to divide 0.7 by the time required for each curve to reach half its initial value.

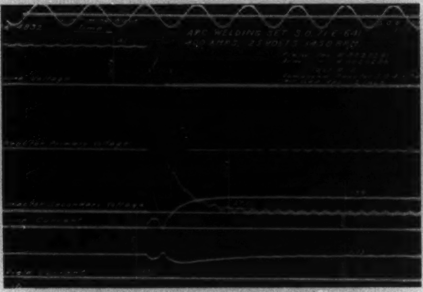

Fig. 6—Oscillogram of Generator Short Circuit Using Flexactor

From the film shown,

$$\frac{1}{T_1} + \frac{1}{T_2} = 12 + 56 = 68$$

And

$$B = \frac{68}{800} = 0.085$$

Also

$$k = \frac{V}{I} = \frac{100}{715} = 0.14$$

Then

$$B/k = \frac{0.085}{0.14} \times 100 \text{ per cent } = 61 \text{ per cent}$$

and the generator is shown to be satisfactory.

In Fig. 6 an oscillogram of the short-circuiting of a generator using a flexactor is shown. This test shows that this machine is satisfactory for a $B$ of 0.342 and that the value of $k$ is 0.295 or the quotient yields the result that the quality of the generator $B/k$ is 116 per cent. The effectiveness of the flexactor in this case is due to using compensation such that the shunt field current actually is increased rather than decreased as a result of decreasing the arc current. This does not mean, however, that an arc can be held, whose length is permanently greater than the limiting value represented by the curve $A^1$ in Fig. 3.

The test described is applicable to all generators using a compound field or its equivalent, including a flexactor; but cannot be applied if the short-circuit current oscillates before reaching its final value. A design that would give an oscillatory current is not usual however. Furthermore, the criteria given are not accurate in case of extreme saturation of the field structure.

The authors wish to thank Doctor J. Slepian for suggestions; and for helpful criticisms of the methods employed in this paper.

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## Discussion

**E. C. Easton:** In their discussion of the arc characteristic, Messrs. Ludwig and Silverman have used Seeliger's equation

$$V = 15.5 + 2.5l + \frac{9.4 + 15l}{i}$$

It might be well to point out that this expression gives only an approximation to the correct form of the characteristic. Experimental evidence now points definitely to the correctness of Nottingham's[1] equation $V = A + \frac{B}{i^n}$ where $A$ and $B$ are constants dependent upon the arc length. When the length of the arc is taken into account it seems probable that the arc characteristic will be of the form[2]

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[1] Nottingham, Jl. A.I.E.E., V. 42, 1923—*Phys. Rev.*, V. 28, 1926.

[2] Myer, *New Studies of Arc Discharge*, A.I.E.E. Trans., March 1933, p. 250.

$$V = \left( \alpha\infty + \frac{(\alpha_1 - \alpha\infty)}{i^n} \right) (1 - E^{-d_1})$$

$$+ \left( B\infty + \frac{(B_1 - B\infty)}{i^n} \right) \left( i - E^{-\left( d\infty + \frac{(d_1 - d\infty)}{i^n} \right) 1} \right)$$

$$+ \left( r\infty + \frac{(r_1 - r\infty)}{i^n} \right) \quad (1)$$

The writers state that near to the welding currents, that is, only over a small range, the arc voltampere characteristic practically is a straight line of the form $A-Bi$. This, to be sure, is true for a small portion of the curve, but for large currents and small arc lengths such as are generally used in welding, the curve is a straight line of zero slope. For example, experiments conducted at Lehigh University by Messrs. Lucas and Easton have shown that for an iron arc 1.17 mm in length the voltage is constant for current values above 40 amperes. See curve *A* in Fig. 1. As the arc length increases, the point at which the characteristic flattens out also advances. However, up to an arc length of about 8 mm this advance is negligible. A set of curves of voltage against arc length taken for currents ranging from 40 to 200 amperes was coincident showing that the voltage across an iron arc must be a function of the arc length but quite independent of current throughout the range of 40 to 200 amperes and up to 8 mm in length.

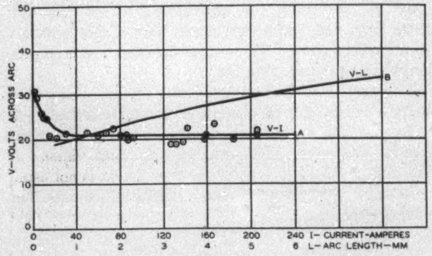

FIG. 1

The average curve of voltage against arc length for currents between 40 and 200 amperes is given as *B* on Fig. 1. This curve is an average of the set of curves shown in Fig. 2. Each of the curves of Fig. 2 is an average of several taken at a certain fixed current. Thus there are 4 curves representing fixed currents of 48, 103, 197 and 151 amperes. The fact that these curves do not lie in any set order with respect to current suggests that the apparent differences are due to experimental error, and that actually all the observed points lead to the average curve *B*. Justification of this assumption lies in the agreement between curves *A* and *B*. Thus at an arc length of 1.17 mm, *B* shows a voltage of 21, while *A* taken at an arc length of 1.17 mm has a limiting voltage of 21 for currents between 40 and 200 amperes. Data for these curves were obtained by measuring the voltage across an arc between 5/8 inch water cooled iron electrodes during very short applications of high current. The arc was started at about 5 amperes and the arc length adjusted by observing the image of the arc enlarged and projected upon a screen. With the arc length properly fixed, high current was passed through the arc for about one-half second. During this short interval, before the electrodes could burn away appreciably, the current and voltage were read. Water cooling was provided to eliminate as far as possible the voltage drop caused by heating of the electrodes. The switching arrangement for applying the high current "shot" is shown in Fig. 4 of a paper entitled *Forces of Electric Origin in the Iron Arc* by Creedy, Lerch, Seal and Sordon, TRANS. A.I.E.E., June 1932, p. 558.

It would seem, therefore, that for normal welding practice, the *B* discussed in this paper should be zero. It would have other values only when considering small currents or long arcs. If *B* is taken as zero, then all but one of the requirements for stability as given in the paper become meaningless. That one requirement is that the condition

$$L_F > \frac{R}{k} \left( \frac{KA}{EK-RA} + 1 \right) M$$

be satisfied. If this condition is satisfied the current will not reverse when going from $\frac{E}{R}$ to $\frac{E}{R} - \frac{A}{K}$ or in other words when going from short circuit value to normal welding value. This requirement, then, is recognized as one similar to that laid down by the Navy specifications. The Navy, however, requires that not only must the current not reverse, but that it must not fall below one third of its short circuit value. It should be emphasized, therefore, that fulfillment of the requirement stated above furnishes only the limiting values of the circuit constants. It does not assure a machine that could satisfy any standard specifications for momentary current fluctuation and arc recovery.

The paper states that if a generator is to be satisfactory during transients the ratio $\frac{B}{K}$ obtained from examination of the machine's operating characteristics must be 60 per cent or more. In connection with this criterion it should be made clear that the *B* calculated for the generator must be greater than the slope of the arc characteristic between the current values of *I* and zero. Any given machine with a ratio $\frac{B}{K}$ greater than 60 per cent is satisfactory only up to an arc voltage below which the slope of the arc characteristic is less than *B*. The ratio $\frac{B}{K}$ alone can not serve as basis for a comparison between generators.

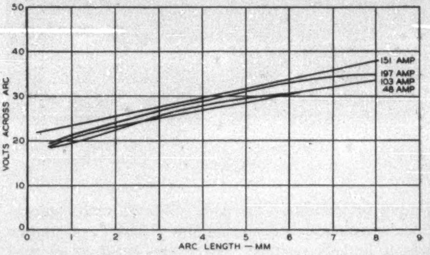

FIG. 2

Another criticism that might be raised is of the authors' use of the concept of arc "inductance." It is not clear how such a condition was conceived. Justification of the use of such a property of the arc demands the discovery and disposition of a definite amount of energy stored in the arc inductance. Since the arc inductance is made part of the circuit constants, its inclusion in this case has not affected the form of the various equations.

Messrs. Ludwig and Silverman have presented an interesting method of determining the stability of arc welding generators. For high welding currents and short arcs $B$ throughout their paper can be taken as zero. With low currents or arcs that may be stretched considerably $B$ must be determined from the circuit characteristic and a reliable expression for the arc characteristic. Unfortunately, at present there are no adequate data available for determination of the latter.

**Frank B. Lucas:** In their discussion of arc characteristics, Messrs. Ludwig and Silverman state that "In oscillograms of arc voltage obtained during welding with iron electrodes, pulsations of high frequency and small magnitude are always observed." They tell us that these pulsations "do not appreciably influence the stability of the arc." On page 561 of the June 1932 TRANSACTIONS of the A.I.E.E. in a paper on forces of electrical origin in the iron arc, Professor Creedy gives oscillograms showing these pulsations and stated that "if one of these oscillations becomes large enough to reduce the current to zero, it can not restart." These oscillograms were taken using storage batteries as a source of power. The oscillations were reduced by using a large self-inductance in series with the arc. It is evident from Professor Creedy's paper that the statement in this paper that the oscillations do not appreciably influence the stability of the arc is true only when the inductance of the circuit is large enough to reduce the size or amplitude of the pulsations to a value less than the current value. Professor Creedy suggests that since "the pulsations do not start at once after the arc is started but only after an interval of time has elapsed they seem to be correlated with the heating of the electrodes." This agrees with Messrs. Ludwig's and Silverman's statement that they have their origin at the cathode.

FIG. 3

In regards to the statement that the voltampere characteristic is practically a straight line of the form $A-Bi$ it has been shown (Creedy, p. 277, TRANSACTIONS A.I.E.E., March 1933) that this characteristic for current values ranging from 50 to 250 amperes is a straight line with zero slope. Therefore the $B$ in this case would be zero, the voltage being independent of the current.

On page 564 of the June 1932 TRANSACTIONS of the A.I.E.E. the writer gave conclusive proof that the process of arc welding can be carried out without short-circuiting the arc. Messrs. Ludwig and Silverman state that "during welding, drops bridge from anode to cathode of the arc, completely short-circuiting it." The writer points out that this is a special case and is not a requisite for electric arc welding.

It is evident that the term "inductance" of the arc used by Messrs. Ludwig and Silverman in their voltage-current equation does not mean inductance. They have used a term already used for a known phenomenon to describe a new, and to the author a doubtful, one. The oscillogram shown in Fig. 3 of this discussion taken by R. Kogge and A. Danello, graduate students at Lehigh University, for 300-cycle a-c arc welding shows that there is no phase displacement between current and voltage as there is when inductance is present. The line $AB$ is drawn to show the path the current curve, curve $C$, would follow if there were no breaks in the curve due to starting. This line shows that the voltage, curve $D$, and current come to zero at the same time.

**L. R. Ludwig and D. Silverman:** Mr. E. C. Easton has called attention to the inability of the Seeliger equation to express accurately the current, voltage, and length relations in the arc. This is quite true, and the substitute relations are much more accurate. But since the conclusions drawn in the paper do not depend on the exact slope of the static arc characteristic curves, they will be unaffected by the use of this equation. The Seeliger equation is used only to show qualitatively the effect on the arc characteristic of lengthening (or equivalent effects).

It is agreed that under certain conditions, such as short length and large currents, the arc drop is reasonably constant over a wide range of current. The value of the steady state $B$ under such conditions may be zero. However, this fact does not alter the conclusions of the paper in regard to the value of $B$ for which the generator is to be designed. For the most difficult condition for the welding generator is not normal decreasing current, but the sudden shifting of arc characteristic from a lower to a higher range of voltage due to some suddenly applied effect such as lengthening. Here the $B$ to be considered is not the steady state slope of either characteristic, but the equivalent or average $B$ of the dynamic characteristic curve which starts from the normal operating point on the lower steady state curve ($V_1$ of Fig. 3 of the paper) and extends to the voltage value which the dynamic curve will reach at zero current as a result of the equivalent lengthening which created the transient. ($V_0$ of Fig. 3.) In the paper, this latter point was obtained by simply extending the straight line portion of the upper steady state curve to the axis. The importance of this point will be evident when it is realized that this phenomenon results from all common disturbances such as lengthening, blowing, dissociation, etc.

The requirements for stability which were given are therefore not meaningless since they depend upon the proper interpretation of the term $B$. Consequently, the conclusion reached by Mr. Easton that only one of the established requirements has any meaning is unfounded in view of his misunderstanding of the meaning of $B$. The one condition acceptable to Mr. Easton is similar to the Navy requirement but the latter is needlessly severe. Regarding the magnitude of $B/K$, the value of 60 per cent has been found to be quite in accordance with observed values. As a result of a number of analyses of welding generator characteristics, those generators which were particularly good welders had values of $B/K$ considerably above 60 per cent; those which were noticeably bad, values below 60 per cent. Generators of average performance had values in the region of 60 per cent.

The use of the term "arc inductance" is not new with the authors. Seeliger makes use of this term and numerous writers in the literature have used it. Unlike the quantity ordinarily denoted by the term "inductance," the arc is not able to store energy and later return it to the circuit, and consequently will not show a displacement between the zero of voltage across and the zero of current through the arc. The term indicates that the voltage across the arc is not a function alone of the arc current, but also of the rate of change of that current. The inductance itself, is not a constant, but depends upon the current and the condition of the arc, being due to the finite time taken for conditions of ionization to change to steady state values for a given current. The value of the arc inductance is the difference in voltage between the transient and steady state arc characteristics, at a given value of current, divided by the rate of change of current at that point. This is shown in the paper.

Mr. F. B. Lucas discusses the high frequency pulsations in arc drop. The basis for the statement that these "do not appreciably influence the stability of the arc" is given in the paper. It is, that with inductance in the circuit it is very improbable that the current will drop suddenly to zero and remain zero. The probability that the inductive voltage appearing across the arc space will restrike the arc is quite high. The use of a storage battery source of power explains why it was not observed in the experiment cited. Commercial welding circuits have more than sufficient inductance to cause restriking in such cases.

The bridging of the welding electrodes by drops of molten metal is not a necessary part of the welding process. It is, however, a common occurrence in welding and whenever present provides a very difficult test of the generator.

# Construction Features of Special Resistance Welding Machines

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***Synopsis.***—*Although the design of so-called standard resistance welders is more or less fixed, the construction of a special resistance welding machine involves a series of design factors which are only approximate and for which one allows large limits. An attempt is made to outline the elementary features of construction for successful operation by enumerating the factors which must be known. A method of obtaining the proper transformer capacity, types of switches for changing the amount of welding current, and means for regulating the time of application of the current are indicated. Important mechanical conditions to be considered are also touched upon.*

*This is followed by a description of the construction features of a few outstanding resistance welding machines of special design used at the Hawthorne Plant of the Western Electric Company. Although most of these machines are of relatively small total current capacities, the current densities used are quite high. The machines described are used for welding precious metal contacts, permalloy wire, bronze brushes, switchboard plug parts and copper rod.*

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THIS paper discusses general construction features of special resistance welding machines and describes a few such machines used at the Hawthorne plant of the Western Electric Company. The material presented is intended to be of some help to machine designers who are primarily concerned with mechanical features of design and to whom welding mechanisms and auxiliaries are more or less troublesome. The paper will also serve as a background for products manufacturers in discussing the building or buying of special process welding machines.

The important operating parts of resistance welding machines are the transformer and its associated circuits, the welding current timing mechanism, pressure members, and the mechanical features peculiar to the particular job.

In building a special welder certain limiting factors of operation and design must be known. The approximate current, voltage, pressure and time required to perform the welding operation are usually determined experimentally on a laboratory set-up or estimated from data obtained by performing a similar operation on another welder. A determination is also made of the sequence and time of operations of handling material, whether performed mechanically or manually.

Having given the approximate secondary current and open circuit voltage, the time of current application, and the interval of time between succeeding operations, limits are set up for transformer capacity. It is well to allow a large factor of safety in capacity as the transformer is relatively inexpensive and additional capacity allows not only for changes in the apparatus being manufactured, but allows for variations in estimated current and circuit impedance of the secondary circuit, which items are very difficult to calculate. For instance, having estimated a required secondary current of 3,000 amperes at an open circuit voltage of two volts for ¼ second, at time intervals of 5 seconds, a transformer might be rated as follows:

"One 10-kva welding transformer, preferably air cooled, capable of delivering a maximum of 5,000 amperes for ¼ second at five second intervals having eleven primary taps to give open circuit secondary voltages of 1.0, 1.2, 1.4, etc., to three volts in 0.2 volt steps."

A relatively large factor of safety in transformer capacity may be criticized, but there are advantages in such procedure that must not be overlooked. In the first place every special welder is somewhat of an experiment and because small changes often upset preliminary calculations, it is well worth while to allow for a larger transformer and make a slightly larger initial expenditure. The ultimate power consumed is not affected, and in addition the welding circuit may be made very high or low in efficiency by the introduction or elimination of ballast impedance to stabilize variations in welding current.

Tap switches in the primary of the transformer circuit used for varying the applied welding voltage are more or less special. Rotary switches usually are used on standard welders, but on special welders such as those built by products manufacturers, a switch made up of standard knife switch parts is simple, inexpensive, easily assembled, and has a high operating efficiency. Fig. 1 shows 3 tap switch circuits often used with welding transformers using knife switches. Circuits *B* and *C* are preferable because at no time are the voltages of any coil combination higher than the applied line voltage. Such switches are inclosed in pressed steel boxes and for additional safety may be protected by a door switch which cuts off the primary feeder circuit when the door is open. On some machines a tap switch is entirely unnecessary as only one operation is performed and a permanent connection prevents tampering with the proper current setting.

The timer switch for regulating the application of welding current is operated usually by a cam and for critical welding operations must have means for adjustment to control the length of time it is closed. On very small machines this switch may interrupt the primary transformer current directly, but on large ones it is only

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an auxiliary control circuit for a large contactor. In recent years the tendency has been toward high current densities for very short intervals of time, and current interruptions as high as 200 a minute may be required. It is very difficult to do this, and other means to accomplish a comparable result are necessary. Circuits are used in which welding currents are greatly reduced instead of interrupted, the time and current being determined by means of a thyratron control circuit or other special transformer winding or magnetic circuit accommodation.

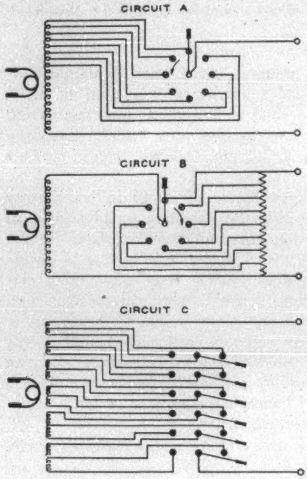

Fig. 1—Tap Switches

The secondary leads from the transformer to electrode holders are made as short as practicable and of a cross-section to allow for air cooling if possible. Leads to movable electrodes may be made of very thin, hard rolled spring bronze or copper and fastened to help the movable electrode advance. Dead copper strips used as movable leads often are a hindrance to good welding operation.

Under important mechanical features are listed the mounting of electrodes, electrode supports, means for cooling these, and application or relief of electrode pressure during the welding operation. One electrode usually is stationary and the other movable, but for automatic feeding of piece parts, it often is necessary to have both movable in order to provide necessary clearances. Movable electrode supports usually are mounted on slides and much care should be taken to make their movement as free as possible and to provide means for proper lubrication. The movable electrodes are actuated nearly always by springs and failure to respond at the proper moment affects the quality of the welded joint. Although cams are often used to move an electrode, a tension or compression spring also is used in conjunction with the same. Proper clearances must be provided around the springs and spring supports to make possible both accuracy and stability of adjustment. Sufficient clearances should also be provided not only for inserting and removing the electrodes, but for dressing them in position. Cooling of electrode tips may be effected by having a large bulk of copper in the electrode or electrode support, by special shapes, or by a compressed air or water cooling system.

Lubrication facilities in connection with electrode parts or any other part of the machine are provided which prevent any oil, grease, or associated dirt from dripping, rubbing or smearing on electrodes.

Appearance and safety of operation are growing steadily in importance. As much as possible of the operating mechanism should be inclosed in a strong housing. All odd ends and corners are hazards and their elimination tends toward greater safety and improvement in appearance. All electrical equipment and wiring must be inclosed, the only allowable exposed portion being insulated operating levers and secondary leads to welding electrodes.

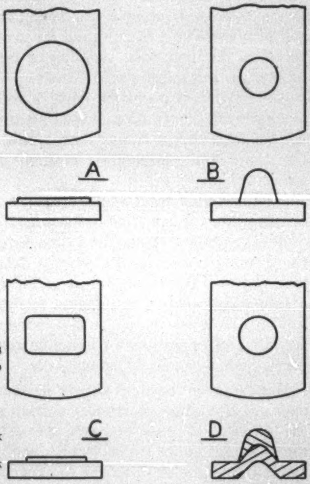

Fig. 2—Precious Metal Point and Disk Contacts

*A*—Disk contact
*B*—Point contact
*C*—Rectangular disk contact
*D*—Embossed disk contact

The feeding of parts to the electrodes may be done directly by hand, by hand fixtures, by rotary table feed, chain feed, or any other standard method of feeding parts in machinery. It is preferable to adapt the feeding mechanism to the welding mechanism because the welding operation usually is the more difficult of the two. The holding fixtures or mechanism for the parts being welded are special in design, whose principal features are proper electrical insulation and convenience of approach to the welding electrodes.

This general discussion is followed at this point by a description of a number of special welders used by the Western Electric Company which illustrate to a large degree the importance of many features previously discussed.

Two important types of machines are point and disk contact welders used to weld precious metal contacts to nickel silver and bronze springs for relays, keys, and other telephone apparatus. Fig. 2 indicates the general form of these contacts, one of each being necessary to make up most pairs, one being called a point and the other a disk contact. Figs. 3 and 4 illustrate the disk and point machines respectively on both of which springs are fed to the welding electrodes by a reciprocating hand fed locating mechanism. On the disk machine, precious metal tape is fed into a miniature punch and die and the proper sizes of contact disks are punched out. Fingers engage these disks and place them in the welding position between the welding electrodes. A forming hammer also is used on this machine to insure a smooth surface on the welded disk. The welded springs are blown from the locating fixture into a chute by a blast of air. The point machine feeds the end of a precious metal wire through a split electrode into contact with a spring. At this point the welding current is applied to fuse the wire end to the spring. Immediately thereafter a cutter snips off the proper length of precious metal, following which a die forms the welded wire into the desired shape. Both machines have a heavy cast iron base and frame for housing transformer and switches, and for mounting the motor and all mechanical operating mechanisms. The transformer tap switch of rotary design is identical for both machines and is mounted in the base of the machine, the operating handle extending vertically upward as shown in Fig. 4, directly in front of the motor. The transformers are rated at 3,700 and 1,700 watts for the disk and point machines, respectively, at a primary operating voltage of 440 volts, a frequency of 60 cycles, and secondary open circuit voltages which vary from 1.2 to 2.8 volts. The motor on each machine is rated at 1/6 hp, 1,800 rpm, 440 volts, 60 cycles, 3 phase, and is geared to the main shaft by 3 reduction gears to give the main operating cam shaft a speed of about 75 rpm. The timer switch for both machines is mounted on the right hand end of the main cam shaft and is shown in detail in Fig. 5. This switch consists of two contact springs using carbon buttons for contact against a carbon block. Pins on each spring engage a double wing cam, one spring making contact against the carbon block and the other breaking contact with the carbon block. Each spring is tensioned in its operating direction of make or break. The springs are mounted on adjustable sliding blocks so that their relation with respect to the cam may be varied to allow a variable setting in the time of application of the welding current. The welding time is about 0.04 second. The wiring diagram of both machines is similar to most resistance welders. Leads from a 440-volt, 60-cycle source feed through a fuse block and three pole rotary snap switch

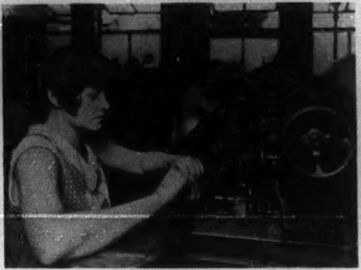

Fig. 3—Semi-Automatic Disk Contact Welding Machine

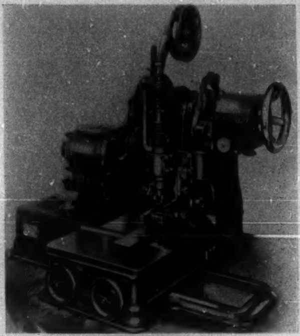

Fig. 4—Semi-Automatic Point Contact Welding Machine

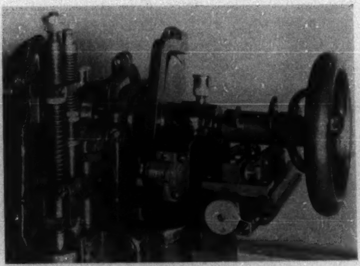

Fig. 5—Contact Welder Timer Switch

to the operating motor and welding circuit. Beyond the 3-pole switch, a 2-pole rotary snap switch separately controls the welding circuit so that the machine may be operated mechanically when the current is shut off. This arrangement also precludes welding circuit operation when the motor is shut off and adjustments are being made by hand.

The welding head of the point machine in Fig. 4 is shown with precious metal wire being fed into it from the large spool at the top. It consists primarily of 3 tube like parts, telescoping each other which are actuated by pivoted levers operated by the cams on the main shaft. The lower end of the center portion supports a pair of grooved split copper electrodes for holding the precious metal wire. A spring moves the wire into the welding position where it is held stationary during the welding operation. For adjustment purposes the grip on the wire may be relieved by the small thumb-operated wing at the very top. The larger spring at the center of the head brings the cutter mechanism to normal, the downward cutting action being supplied by means of the cam operated lever directly above the lock nuts of the spring.

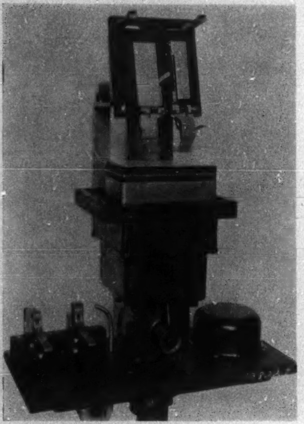

FIG. 6—BUTT WELDER FOR 0.011 PERMALLOY WIRE

Cam operated levers actuate the forming hammer located behind the welding head, and the sliding carriage which brings the work under the welding head. These operating cams are covered by a sheet metal hood not shown in the picture.

The disk welding machine is similar to the point welder except for its welding head and method of feeding the precious metal contacts. The disks are cut from precious metal tape by the small punch and die indicated in Fig. 3. The tape is fed forward by a small clutch and feeding device actuated by the spring carriage slide. The split finger shown, holds the disk and brings it between the welding electrodes at the same time the carriage brings a spring between them. The forming hammer at the front part of the head backed by an adjustable spring is used to surface the disks on the anvil immediately below.

The electrodes on the disk machines are very similar to the conventional design of spot welder, the lower one being stationary, and the upper one being movable and backed with an adjustable spring. Flexible copper strip sheet of dimensions 0.005 in. by 1 in. built up to a thickness of 1/8 in., is used for the jumper leads to the movable electrodes to carry a maximum current of 1,500 amperes. The rest of the secondary leads are bar copper whose minimum cross-sectional area is about 1/8 in. by 1¼ in.

The point machine lower electrode is a comparatively large rectangular surface block-like shape, which is hinged and backed by a spring for a quick follow-up during the welding operation. The upper electrode is a split pencil like shape through which wire is fed in a manner similar to feeding lead in an automatic pencil. The upper electrode is stationary during the welding operation. The secondary leads from the transformer have a cross-sectional area of about 1/8 in. by 5/8 in. for a maximum current of 800 amperes.

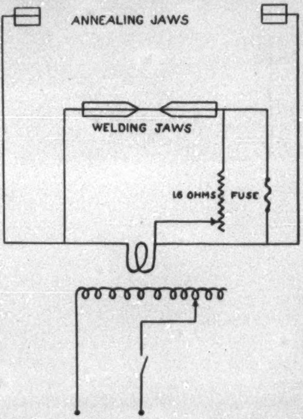

FIG. 7—WIRING DIAGRAM OF PERMALLOY BUTT WELDER

Fig. 6 shows a butt welder rebuilt from a copper wire brazing unit used in welding 0.011 in. permalloy wire under carbon tetrachloride because welded joints made in air were brittle and unsuitable for drawing. The jaw mechanism is made of monel metal to prevent corrosion and is of very light construction. The right jaw is movable and actuated by a vertical blade spring. Fig. 7 shows the wiring diagram of this welder. The secondary circuit has a resistance ballast in series with the welding jaws which serves both as a timer, a current tapering device, and an auxiliary annealing circuit. The resistance ballast is made up of a variable resistance of about 1.6 ohms and a 0.008 in.—2 in. nickel fuse connected in multiple. The transformer is rated at 150 watts, has an open circuit voltage of 3 volts, and delivers about 100 amperes during the welding operation. The wire ends are clamped in the welding jaws, spaced at 0.066 in., immersed in carbon tetrachloride by raising the container to the jaws, and the current sent through the circuit. In an instant the wire ends become plastic, the nickel fuse blows, the current is reduced, and the jaws move together to a distance of 0.033 in. As long as the welding key is depressed, the reduced current flows through the joint. Approximately 3 in. of wire on either side of the weld is annealed in the annealing terminals shown at the extreme top of Fig. 6 to prevent strains in handling the softer material directly adjacent to the weld. The joints are very strong and after the welding flash is removed, may be drawn through wire reducing dies. Small nichrome, chromel, perminvar, and iron and constantin thermo-couple wires, can easily be joined on this machine.

FIG. 8—COPPER ROD WELDING MACHINE

Fig. 8 shows a specially constructed copper rod welder in use at the Western Electric Company wire drawing plants. The operation of these machines are similar to most butt welders. High current densities ranging in value from 0.2 to 0.4 amperes per circuilar mill and applied for very short intervals of time, are used to make joints suitable for drawing. For stabilizing the welding current an impedance ballast is used in the secondary circuit. Rod ends are cut square by means of a circular saw operated by the foot pedal at the left of the machine. This insures good contact and practically eliminates so-called contact resistance. The stationary and movable jaws are made of aluminum bronze of very sturdy construction. Long clamping arms give a good leverage and make for good contact between the rod and copper die blocks. The movable jaw slide is fitted very carefully and leads thereto are carefully mounted in order to have the jaw movement properly coordinate with the heating cycle during the welding operation. The total movement of the jaw is about ¼ in. at an initial pressure of about 150 lb for ¼ in. rod.

FIG. 9—WELDING MACHINE WITH CONVEYOR FOR 109 AND 110 SWITCHBOARD PLUGS

The transformer is capable of delivering nearly 30,000 amperes and has open circuit secondary voltage taps ranging from 4 to 11 volts in one-half volt steps. Rod diameters of ¼ in. to 3/8 in. may be successfully welded with such capacity. No tap switch is used with the transformer, not only because the same size rod is always welded, but to prevent operators from tampering with the setting. The current to the welding transformer is controlled through a 200-ampere contactor switch by means of a timer switch linked up to cut off after the movable jaw has moved about 0.035 in. A foot pedal switch operates the control circuit after a safety switch on the movable jaw spacing lever has been closed by releasing the spacing lever. The entire hous-

FIG. 10—SEMI-AUTOMATIC WELDING MACHINE FOR MULTIPLE BRUSH SPRINGS

ing has been made very heavy to withstand extreme rough usage.

Fig. 9 shows a punch press type machine for welding switchboard plug centers shown in the foreground. The outstanding feature of this machine is the chain used for bringing the welding fixtures into position. Two separate joints are made in each fixture by two transformers separately controlled and adjusted by timing cams and rotary tap switches, respectively. The press mechanism and fixtures are split so that separate pressures and separate adjustment can be had for either joint. Two 7.5-kva transformers with open circuit secondary voltages of 1 to 3 volts in 0.1-volt steps furnish welding current on this machine.

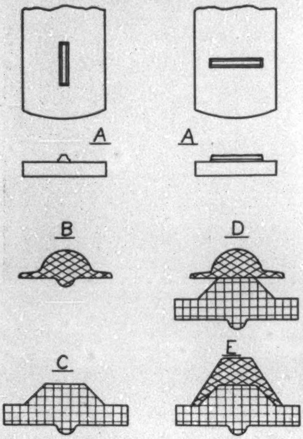

Fig. 11—Cross-Bar Bimetal Contacts

*A*—Cross bars welded to springs
*B*—Contact metal shape
*C*—Base metal shape
*D*—Welded bimetal
*E*—Welded bimetal after rolling

Fig. 10 shows a recently developed welder used for welding multiple brush springs. Each spring consists of an offset piece of 0.015 in. nickel silver about ¼ in. wide and 2 in. long to one end of which is welded a 0.025 in. bronze shoe about 0.075 in. wide by 3/8 in. in length. A longitudinal section shows the shoe to have a *Z* bar shape, one end of which is welded to the flat surface of the spring and the other end of the body is projection welded to an offset part of the spring. Fiber insulators placed between the two joints make the welding operation difficult and for that reason special provisions have been made to make each weld separately by separate transformer circuits.

This machine consists primarily of a rotating ring for holding the parts to be welded and advancing them in successive steps to the welding electrodes. Two operators place the nickel silver springs in holders and one operator feeds the bronze shoes into a chute which slides them to the proper location on the spring end over the fiber insulator. As on the switchboard plug machine the two welded joints are made by separate welding heads each of which has its individual electrodes, pressure system, transformer, and control. The transformers and timing arrangements are the same as those on the disk contact machine previously described.

Fig. 11 shows sections of a cross-bar type bimetal contact tape, short lengths of which are welded to nickel silver springs. The tape consists of an upper layer of contact metal and a lower layer of base metal. The cross sections, *B*, *C*, *D* and *E*, illustrate how this bimetal is produced. Contact metal wire and base metal wire, respectively, are rolled into the cross-sectional shapes, shown under *B* and *C*. These two tapes are welded together on a roll type welder to the shape shown under *D*, the current being localized in the welding ridge on the lower side of the contact metal tape. After the welding operation, the bimetal tape is passed through rolls and given the final shape, shown by sketch *E*. The bimetal tape is fed into an automatic machine, cut to the required bar length and welded to springs in positions shown by *A*.

Fig. 12 is a diagrammatic sketch of the continuous welding machine for welding sections *B* to *C* to form section *D*. It consists essentially of two heavy electrode copper grooved rolls for feeding the two tapes in the welding position as a welding current of about 1,200 amperes is passed through them. The axis of the lower roll is fixed while the upper roll corresponds to a movable electrode pivoted as shown. Current is fed to the rolls from adjacent copper disks upon which brushes of conventional low voltage generator design are placed. Spring pressure for the welded joints is regulated by means of a spring adjustment which counter-balances the weight of the floating upper electrode. The bimetal tape is produced at the rate of about 8 feet per minute and a separate weld is produced for each half cycle of 60-cycle welding current. A transformer rated at 2 kva having open circuit secondary voltage taps of 0.9 volt to 1.7 volts in 0.1 volt steps gives ample current

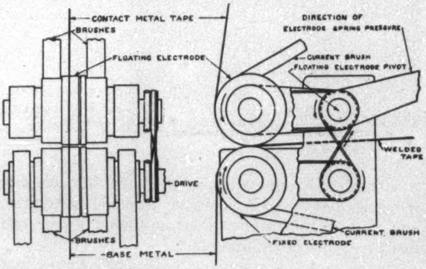

Fig. 12—Continuous Tape Welder

adjustment for this work. Micrometer adjustments are necessary for alignment purposes and distance limit spacing between the rolls.

In conclusion one may state that good welding machines are designed around the welding mechanism; construction limitations being imposed by the nature of the weld itself, the parts being welded, the feeding mechanism, the transformer and associated circuits, the pressure members, the timing interval and its effect on speed and inertia limits of moving parts, safety features, and methods of lubrication. No one of these is outstandingly important, yet each is important in itself. The problem resolves itself into one of careful coordination.

# The Life of Impregnated Paper

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## INTRODUCTION

IT is generally agreed that the most important factor limiting the life of the so-called solid type of impregnated paper insulated cable is internal ionization in voids or gas pockets, commonly due to expansion and contraction under temperature cycles, or less commonly, to impregnation originally imperfect. Gaseous ionization leads to well known rapid heating and destructive action on both oil and paper. Under its influence the original sealing action of the oil is lost, the original paper structure is destroyed, both in such mutually cumulative relation as to lead rapidly to breakdown.

Efforts to increase the life of such cables therefore have been of two general types: (1) the search for materials which will withstand gaseous ionization without injury; and (2) the suppression or elimination of ionization.

In the first type of effort an enormous amount of work and expenditure of money has been directed to studies of wax formation, ionic bombardment, and allied phenomena in oils and in oil mixtures, in search for a compound which is most nearly proof against the action of ionization. Apparently the point of view in these studies is that gaseous ionization is necessarily inherent in the solid cable and that it should be possible to discover materials which are not damaged thereby. It cannot be said that the results of this large amount of work have been very encouraging. Some knowledge has been acquired as to the probable causes of wax formation and some differences in the behavior of various oils have been found. No compound of outstanding resistance to ionization has been found, however, nor in view of the inherent chemical instability of oil and the susceptibility of paper fiber to oxidation can it reasonably be expected that a radical improvement will be found in this direction.

Far more promising, however, are the results attained in the suppression and elimination of internal gaseous ionization. The most obvious measures are the restriction of voltage stress and temperature elevation to such values as, based on practise and experiment, are certain to limit the intensity of ionization to such values as will permit a reasonable life of the cable. These are the measures commonly adopted for solid cables and they have therefore imposed definite limitations upon their capacities and voltage ratings.

Next in order of importance as limiting ionization is the shielded or type *H* cable. This improvement is based on sound principles since it limits the volume of insulation exposed to ionization without interference with the normal insulating function, and at small cost. It does not however, attack the essential limitation of the solid cable, namely the occurrence of gas voids in the body of the insulation wall.

The most recent and most important improvement in the direction of the suppression of ionization is the so-called oil-filled principle in which by the use of oil channels and thin oils, it is aimed to furnish a sufficient supply of oil at all times and at all places to prevent any tendency to the formation of gas voids resulting from temperature variation.

Of the relative value of the two classes of effort just described, for the increase of the life of cables, there can be no question of the outstanding importance of the second group, and particularly of the oil-filled principle. The remarkable improvements in ionization characteristics and the increases in current and voltage ratings of cables of the type *H* and oil-filled types on the one hand, and the failure to find refractory materials or preventive measures in the solid type of cables on the other hand, clearly demonstrate the directions in which improved cable performance must be looked for. In this statement it will be understood that we are considering the possibilities offered by underlying physical principles only, and have not introduced consideration of the economic element of relative cost. The relatively lower cost of the solid cable and clear knowledge of its limitations will insure probably for always its wide use in the lower voltage ranges. But for increased current capacities, higher voltages, and higher temperatures, the oil-filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely.

The dominant influence of internal ionization on the life of solid cables has overshadowed the question of a possible inherent influence of the impregnating oil itself on the life of impregnated paper. As a consequence, this question has received little or no experimental study. Specifications for a cable oil are limited usually to values of low voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity as related to the purchasers' or manufacturers' ideas of its bearing on permanence of impregnation. By sufficient care in refinement, it is possible to meet these specifications with a very wide variety of oils and as a consequence this variety in fact extends itself in considerable measure to the cable oils now in use.

In the oil-filled cables so far installed and operated, the oils employed have been limited to only one or two grades, and there is no knowledge as to the inherent properties which have given them their value, nor has any comparative study been made looking to a determination of important oil characteristics and the relative

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behavior of the large number of available oils. It is high time, therefore, that studies of this character be begun.

## THE MATERIALS AND TEST SAMPLES

This paper reports the results of a series of accelerated life tests on impregnated paper samples in which effort has been made to eliminate all variable factors and conditions except those pertaining to the oil. To this end a single paper has been used, and all test samples assembled, dried, evacuated, and impregnated as nearly as possible under identical conditions. The impregnation program adopted aimed at practically complete impregnation, so that gaseous ionization would be eliminated as an important factor in the life of the samples. This result seems to have been attained as will appear. With gaseous ionization either absent or reduced to very low terms, it is believed that the interesting differences which have been found in the behavior of the various oils are inherent either in the properties of the oils themselves or in the relation of these properties to the structure of the paper.

*The Paper.* The same grade of wood pulp paper tape as furnished to the cable trade by a well known manufacturer was used in all the samples. It was not supercalendered and had the following characteristics:

| | |
|---|---|
| Thickness | 0.004 in. (1.016 cm) |
| Width | 1 in. (2.54 cm) |
| Specific gravity | 0.937 |
| Gurley air resistance | 640 sec |
| Effective capillary radius | 8.2 by $10^{-6}$ cm |
| Conductivity (dry) | 9.5 by $10^{-16}$ mhos per cucm |

All at 25 deg C

*The Oils.* Fourteen different oils have been studied, as furnished by four manufacturers. Some description of the oils and their principal physical constants are given in Table I. The oils for the most part, are those offered to the cable trade. Exceptions are No. 104 and notably Nos. 109 to 113, these latter having been prepared by a well known refiner as having special characteristics for these experiments. In connection with most of these oils it has not been possible to secure complete information either as to their origins, their programs of refinement, or their principal chemical characteristics. This applies particularly to those oils which now are sold to the cable trade. As may be seen, most of the oils are those commonly employed for solid core cables. Three, however, Nos. 104, 108 and 113, are thin oils such as used in oil-filled cables. The differences in viscosity in these two groups are quite wide.

Most of the oils were shipped to us protected by an atmosphere of carbon dioxide or of nitrogen. This condition was maintained by us and at no time before completion of the impregnated sample was the oil exposed to the air. Before admission to the impregnating tank, the oil was sprayed into a vacuum of 1 mm Hg, passing down over a series of cones to a heating tank where it was elevated to a temperature of 60 deg under vacuum, and thereafter drawn into the impregnating tank. The d-c conductivity and dielectric strength of the oil was measured both before and after this treatment. A substantial lowering of conductivity, and an increase of dielectric strength was found in practically all cases. (See Table I.)

*The Impregnated Samples.* Each sample consisted of 16 layers of the 0.004 in. paper spiralled in cable fashion with butt joints and with one-fourth width overlap, on a 2.5-cm diam smooth brass tube as high voltage electrode. The outer or measuring electrode (60.96 cm long) was of lead foil reenforced with thin sheet lead. This electrode was protected by guard rings and ends of reenforced insulation. Both high voltage and measuring electrodes were perforated at wide intervals with very small holes to facilitate impregnation. Drying, evacuation, and impregnation were carried out at 2 mm Hg

TABLE I—OIL PROPERTIES

| Oil No. | Base | Pour point °C | Flash point °C | Specific gravity 40° C | Viscosity poises 40° C | Surface tension dynes/cm. 40° C | Penetrative power $\times 10^{-3}$ (Kraft) 40° C | Dielectric stgt-volts | | 20 min. cond. mhos/cc $\times 10^{-14}$ 40° C | | P.F. of imprg. sample 40° C | Life at 400 v/m (avg. of 20 mm. sets) hr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Before trmt. | After trmt. | Before trmt. | After trmt. | | |
| 100 | Undewaxed paraffin | 35.0 | 274 | 0.8788 | 7.5 | 51.8 | 5.57 | 20,175 | 27,960 | 105.0 | 34.2 | 0.00275 | 1,118 |
| 101 | Paraffin | 15.7 | 296 | 0.881 | 5.7 | 31.2 | 5.0 | 16,864 | 25,850 | 605.0 | 218.0 | 0.00353 | 974 |
| 102 | Semi-refined naphthene | − 7.0 | 288 | 0.9268 | 7.2 | 20.1 | 3.55 | 19,931 | 29,827 | 1,630.0 | 1,313.0 | 0.00483 | 2,948 |
| 103 | Naphthene (phenol extract) | 19.3 | 255 | 0.96 | | | | 14,670 | 25,620 | 11,900.0 | 6,400.0 | 0.00872 | 20.8 |
| 104 | Highly refined white oil | 0.0 | | 0.83 | 0.132 | 32.0 | 33.0 | 31,100 | 31,550 | 1.4 | 1.0 | 0.00264 | 12,882 |
| 105 | Dewaxed paraffin | − 7.0 | 282 | 0.8829 | 4.9 | 31.3 | 5.47 | 17,552 | 25,500 | 322.0 | 84.8 | 0.00276 | 1,599 |
| 106 | 75% No. 105 25% rosin by wht | 4.4 | | 0.935 | 17.5 | 21.6 | 2.28 | 27,660 | 28,845 | 130.0 | 149.0 | 0.00282 | 1,096 |
| 107 | Highly refined paraffin | 4.4 | 263 | 0.903 | 4.07 | 38.3 | 6.52 | 27,837 | 28,820 | 7.34 | 5.75 | 0.00258 | 1,053 |
| 108 | Refined light oil | −29.0 | 149 | 0.8805 | 0.1602 | 28.2 | 28.2 | 27,640 | 26,990 | 12.6 | 24.8 | 0.0027 | 9,081 |
| 109 | Highly refined naphthene | − 6.7 | 271 | 0.9015 | 2.46 | 33.0 | 7.67 | 18,410 | 27,790 | 32.4 | 22.0 | 0.00238 | 7,146 |
| 110 | Refined naphthene | − 7.0 | 294 | 0.903 | 4.82 | 32.8 | 5.48 | 21,600 | 31,710 | 47.1 | 22.8 | 0.00261 | 2,568 |
| 111 | Paraffin blend | − 4.0 | 202 | 0.8693 | 0.368 | 32.9 | 19.5 | 27,150 | 27,763 | 103.0 | 74.3 | 0.00376 | 6,510 |
| 112 | Paraffin blend | − 2.0 | 218 | 0.878 | 0.878 | 32.9 | 12.85 | 29,400 | 33,540 | 7.9 | 5.4 | 0.00309 | 1,929 |
| 113 | Refined naphthene | −17.8 | 190 | 0.891 | 0.37 | 30.3 | 18.96 | 29,520 | 30,975 | 81.7 | 61.2 | 0.00289 | 14,304 |

pressure in the standard specimens for life test. After impregnation in the vacuum tank, the specimen was transferred to the high voltage test box containing three open oil tanks. The test specimens were made in sets of 3, and 1 specimen was placed in each of the oil boxes and immersed in the oil in which it was impregnated. The oil tanks were themselves deeply immersed in an outer bath of circulating oil permitting temperature adjustment between 25 deg and 80 deg. The whole assemblage of test tanks was enclosed in a large outer wooden box with thermal insulation, through which high voltage porcelain bushings permitted connection of the test specimens to the high voltage source. More detailed descriptions of the test samples as well as of the methods of drying, impregnation, measurement of power factor, temperature, loss, voltage, life, etc., have been given in a foregoing paper.[1]

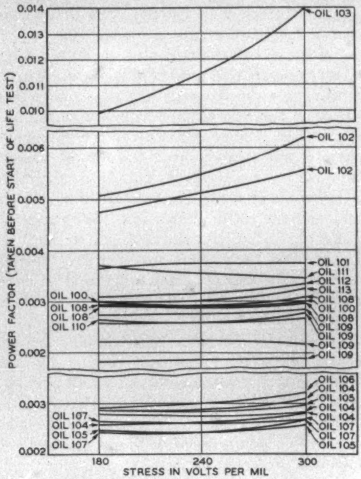

FIG. 1—POWER FACTOR—VOLTAGE CURVES

Kraft paper—various oils
Standard construction and treatment 40 deg C

## MEASUREMENTS, TESTS, AND RESULTS

The d-c conductivity and the dielectric strength of each oil was measured as received and after the vacuum treatment referred to above. Measurements were also made of the viscosity and surface tension and the penetrative power,[2] or capillary constant, in each case, the results being given in Table I. The power factor and initial or short time conductivity measurements were made on several of the oils, the values for which, and their significance as bearing on dielectric loss in the impregnated sample and other discussion, have been given in a separate paper.[3]

The impregnated specimens were constructed in sets of 3; usually 2 such identical sets were tested for each oil; often there were 3 sets and sometimes more. Before the life test, measurements of power factor, as related to voltage in the range 180-300 volts per mil and at 40 deg C were made on each of the 3 specimens of 1 set. The results of these tests are assembled in Fig. 1. Also in each case power factor at 180 volts per mil was measured over the temperature range 25 deg-80 deg C. The results of these tests are given in Fig. 2. Power factor at 180 volts per mil was also read at intervals during the life tests as given in Fig. 3 for the entire series of tests, and in Figs 4 and 5 for special cases.

In the accelerated life tests (150 in all) each sample was tested singly, being taken one by one from the impregnating chamber within which an atmosphere of nitrogen at atmospheric pressure was maintained. The life test was started at 400 volts per mil, maintained for one hour, then 500 volts per mil for one hour, then 600 volts per mil for 10 hours, 650 volts per mil for 10 hours, 700 volts per mil for 37 hours, 750 volts per mil for 40 hours, 800 volts per mil for 40 hours, 850 volts per mil to failure. These tests were made at 40 deg C, this value being maintained within a fraction of a degree by automatic means.

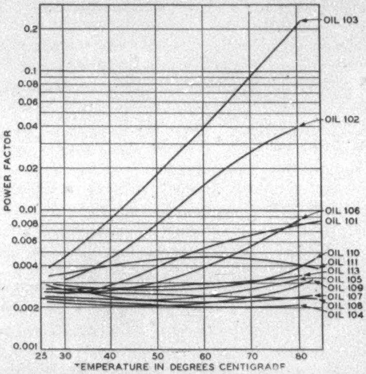

FIG. 2—POWER FACTOR TEMPERATURE CURVES

Kraft paper samples impregnated with various oils. Power factor measured at 180 volts per mil

The results of the life tests on all the oils are summarized in Tables II and III. Table II reports those oils either known to be or believed to be of so-called paraffin base, and as furnished by several different refiners, and Table III, a special group of oils developed for these tests by one refiner and all stated to be of naphthenic base. Exact information as to the origins and differences

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1. For references see bibliography.

## TABLE II—PARAFFIN OILS

Accelerated Life Test History of 2.0 mm Hg Sets

| Oil | Specimen | Number of hours at: (volts per mil) | | | | | | | | Total No. hours | Avg. No. hours | Avg. life at 400 v/m hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 400 | 500 | 600 | 650 | 700 | 750 | 800 | 850 | | | |
| | KK-1 | 1 | 1 | 10 | 3.4 | | | | | 15.4 | | |
| 100 | KK-2 | 1 | 1 | 10 | 10.0 | 19.3 | | | | 41.3 | 24.4 | 1,118 |
| | KK-3 | 1 | 1 | 10 | 4.5 | | | | | 16.5 | | |
| | S-1 | 1 | 1 | 10 | 10.0 | 5.5 | | | | 27.5 | | |
| 101 | S-2 | 1 | 1 | 10 | 10.0 | 5.6 | | | | 27.6 | 23.6 | 974 |
| | S-3 | 1 | 1 | 10 | 3.7 | | | | | 15.7 | | |
| | H-2 | 1 | 1 | 10 | 10.0 | 37.0 | 40.0 | 1.5 | | 100.5 | | |
| | H-3 | 1 | 1 | 10 | 10.0 | 37.0 | 40.0 | 30.8 | | 129.8 | | |
| 104 | I-1 | 1 | 1 | 10 | 10.0 | 37.0 | 11.0 | | | 70.0 | 106.1 | 12,882 |
| | I-2 | 1 | 1 | 10 | 10.0 | 37.0 | 30.7 | | | 89.7 | | |
| | I-3 | 1 | 1 | 10 | 10.0 | 37.0 | 40.0 | 40.0 | 1.5 | 140.5 | | |
| | N-1 | 1 | 1 | 10 | 10.0 | 6.6 | | | | 28.6 | | |
| | N-2 | 1 | 1 | 10 | 9.0 | | | | | 21.0 | | |
| 105 | N-3 | 1 | 1 | 10 | 10.0 | 31.2 | | | | 53.2 | 31.6 | 1,599 |
| | P-1 | 1 | 1 | 10 | 10.0 | 8.5 | | | | 30.5 | | |
| | P-2 | 1 | 1 | 10 | 10.0 | 7.9 | | | | 29.9 | | |
| | P-3 | 1 | 1 | 10 | 10.0 | 4.5 | | | | 26.5 | | |
| | CC-3 | 1 | 1 | 10 | 10.0 | 4.4 | | | | 26.4 | | |
| 107 | HH-1 | 1 | 1 | 10 | 10.0 | 1.7 | | | | 23.7 | 25.7 | 1,053 |
| | HH-2 | 1 | 1 | 10 | 10.0 | 4.0 | | | | 26.0 | | |
| | HH-3 | 1 | 1 | 10 | 10.0 | 4.7 | | | | 26.7 | | |
| | EE-1 | 1 | 1 | 10 | 10.0 | 37.0 | 40.0 | 1.4 | | 100.4 | | |
| 108 | EE-2 | 1 | 1 | 10 | 10.0 | 37.0 | 14.1 | | | 73.1 | 91.6 | 9,081 |
| | EE-3 | 1 | 1 | 10 | 10.0 | 37.0 | 40.0 | 2.2 | | 101.2 | | |
| | SS-1 | 1 | 1 | 10 | 10.0 | 37.0 | 11.2 | | | 70.2 | | |
| | SS-2 | 1 | 1 | 10 | 10.0 | 37.0 | 15.3 | | | 74.3 | | |
| 111 | SS-3 | 1 | 1 | 10 | 10.0 | 37.0 | 7.3 | | | 66.3 | 75.5 | 6,510 |
| | TT-2 | 1 | 1 | 10 | 10.0 | 37.0 | 10.0 | | | 69.0 | | |
| | TT-3 | 1 | 1 | 10 | 10.0 | 37.0 | 38.7 | | | 97.7 | | |
| | VV-1 | 1 | 1 | 10 | 10.0 | 23.0 | | | | 45.0 | | |
| 112 | VV-2 | 1 | 1 | 10 | 10.0 | 8.5 | | | | 30.5 | 35.4 | 1,929 |
| | VV-3 | 1 | 1 | 10 | 10.0 | 8.8 | | | | 30.8 | | |
| | XX-1 | 1 | 1 | 10 | 10.0 | 21.3 | | | | 43.3 | | |
| 105 | XX-2 | 1 | 1 | 10 | 10.0 | 25.8 | | | | 47.8 | 54.8 | 3,904 |
| (At 70° C) | XX-3 | 1 | 1 | 10 | 10.0 | 37.0 | 14.2 | | | 73.2 | | |
| | AA-1 | 1 | 1 | 10 | 10.0 | 3.9 | | | | 25.9 | | |
| 106 | AA-2 | 1 | 1 | 10 | 10.0 | 10.6 | | | | 32.6 | 26.8 | 1,176 |
| | AA-3 | 1 | 1 | 10 | 9.9 | | | | | 21.9 | | |

## TABLE III—NAPHTHENE OILS

Accelerated Life Test History of 2.0 mm Hg Sets

| Oil | Specimen | Number of hours at: (volts per mil) | | | | | | | | Total No. hours | Avg. No. hours | Avg. life at 400 v/m hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 400 | 500 | 600 | 650 | 700 | 750 | 800 | 850 | | | |
| | V-1 | 1 | 1 | 10 | 10 | 37.0 | 10.8 | | | 69.8 | | |
| | V-2 | 1 | 1 | 10 | 10 | 21.6 | | | | 43.6 | | |
| | MM-1 | 1 | 1 | 10 | 10 | 37.0 | | | | 59.0 | | |
| 102 | MM-2 | 1 | 1 | 10 | 10 | 7.7 | | | | 29.7 | 45.9 | 2,947 |
| | MM-3 | 1 | 1 | 10 | 10 | 19.8 | | | | 41.8 | | |
| | NN-1 | 1 | 1 | 10 | 10 | 3.0 | | | | 25.0 | | |
| | NN-2 | 1 | 1 | 10 | 10 | 16.5 | | | | 38.5 | | |
| | NN-3 | 1 | 1 | 10 | 10 | 37.0 | 1.0 | | | 60.0 | | |
| | OO-2 | 1 | 1 | 10 | 10 | 37.0 | 6.3 | | | 65.3 | | |
| | OO-3 | 1 | 1 | 10 | 10 | 37.0 | 17.5 | | | 76.5 | | |
| 109 | PP-1 | 1 | 1 | 10 | 10 | 37.0 | 40.0 | 5.2 | | 104.2 | 78.5 | 7,146 |
| | PP-1 | 1 | 1 | 10 | 10 | 37.0 | 33.7 | | | 92.7 | | |
| | PP-3 | 1 | 1 | 10 | 10 | 32.0 | | | | 54.0 | | |
| | RR-1 | 1 | 1 | 10 | 10 | 26.5 | | | | 48.5 | | |
| 110 | RR-2 | 1 | 1 | 10 | 10 | 5.0 | | | | 27.0 | 42.7 | 2,568 |
| | RR-3 | 1 | 1 | 10 | 10 | 30.4 | | | | 52.4 | | |
| | WW-1 | 1 | 1 | 10 | 10 | 37.0 | 40.0 | 12.3 | | 111.3 | | |
| 113 | WW-2 | 1 | 1 | 10 | 10 | 37.0 | 28.0 | | | 87.0 | 113.3 | 14,304 |
| | WW-3 | 1 | 1 | 10 | 10 | 37.0 | 40.0 | 42.6 | | 141.6 | | |

in processes of refinement has been withheld in all cases. It will be noted from Tables II and III that the complete history of the test as regards the duration of life at each value of stress, together with the total life of each sample, and the average life of the entire group for each oil, are given. Moreover in the last column the average life per group as reduced to 400 volts per mil by the 8th power law is also given. As is well known in breakdown tests of this character, there is usually a fairly wide variation in the results as observed on successive similar samples. We have not escaped this difficulty and in the results as reported we have had to use our judgment as to the weight to be attached to life values of individual specimens falling well away from the average value pertaining to the group. As indicative of the results of individual tests we note as of average uniformity set SS, oil No. 111 giving 5,706, 6,322, 5,119 hours at 400 volts per mil respectively. One of the poorer examples as regards spread of results was Set MM, oil No. 102, giving 4,004, 1,427, 2,494 hours respectively, at 400 volts per mil. In the curves and figures as reported, the values are the average values (see Table III) of groups of 3, 6, or 9, as the case may be, with occasional elimination of one apparently abnormal specimen.

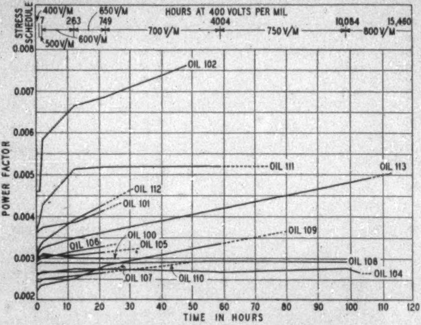

Fig. 3—Power Factor—Time Curves

Representative samples, each oil power factor measured at 180 volts per mil. Life test at 40 deg C

The collected results of the life tests, as based on the average performance of all specimens tested are shown in Fig. 3 in which the horizontal scale is the actual life in hours and the vertical scale gives the power factor at 180 volts per mil, as measured at intervals during the life run. At the top of the figure successive increments of stress and the duration of each are also given. Each curve refers to a single oil. The dotted sections show the life after the last measurement of power factor. If the values of life are reduced to 400 volts per mil, say by the 8th power law, the differences amongst specimens as reported with the various oils are much more pronounced than as indicated in Fig. 3.

A more intimate picture of the change of power factor during the life test is given in Figs. 4 and 5 as taken for single samples. In these the horizontal scale is again linear in actual hours of test. Fig. 4 is typical of those specimens having relatively long life with no material change in power factor until the very last stages within which the rise in power factor is very rapid. Fig. 5 shows a slow and uniform rise of power factor throughout a relatively long life followed by a rapid rise in the last stages of the approach to breakdown. Fig. 5 also shows the temperature variation in the oil just outside the specimen, upper curve, and that inside the tube forming the high voltage electrode. As a general thing these two temperatures were closely the same except in the last stages of life when the losses were increasing rapidly and when the difference would sometimes rise to 4 deg or 5 deg.

Of the total number of breakdowns observed 97 per cent occurred under the central electrode. A few occurred under the guard electrodes, and one or two failures under the reenforced ends have not been recorded. The failures for the most part were clean punctures, perhaps a millimeter or more in diameter at the inner and outer electrodes and 5 millimeters in diameter and often smaller within the insulation wall, usually with some adjacent scorching, dendrites, and gas formation. Conditions throughout the sample after failure generally were uniform longitudinally, although there was often a pronounced variation in the amount of gas formation radially through the thickness of the insulation wall. In general the appearance of the samples after failure was such as to indicate that the deterioration leading to failure was quite uniform over the whole length of the sample. One of the striking features evident on dissection, particularly in the paraffin oil samples, was the presence, practically in every case, of gas, uniformly distributed through 4 or 5 layers and the further fact that the occurrence of this gas was limited to the last stages

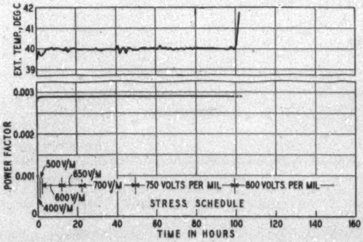

Fig. 4—Power Factor—Temperature—Time Curves

Spec. EE-3 compound No. 108
Power factor measured at 180 volts per mil 40 deg C

of life. The amount of this gas was definitely less in the naphthene group. A number of samples of both types of oil were opened after long life and before approach to failure. No gas was ever found in these specimens. Furthermore, a number of specimens were carried to 800 volts per mil, maintained at this stress for a number of hours and then removed without failure. No gas was found in these specimens. No wax has ever been found in any of the specimens. These facts lead us to feel that gaseous ionization in the ordinary acceptance of the term was not present in any of these specimens and that impregnation, in the ordinary sense of the term, that is to say, complete absence of visible gas, was complete.

## DISCUSSION

*Power Factor.* The power factor values given in Figs. 1 and 2 indicate a fairly wide variation both in value and type of behavior of the oils. The high values and rising character of the curves for oils No. 102 and No. 103 are in some measure accounted for by the fact that these naphthene base oils were not as thoroughly refined as some of the paraffin base oils submitted to the cable trade by the same manufacturer. Oils No. 109, 110, and 113 are more highly refined oils from the same base as No. 102. With this in mind, it may be seen that the variation in power factor values over the whole temperature range studied is relatively small for the entire series of oils. It will be noted also that the variation of power factor with stress is very small over the whole group, up to 300 volts per mil, thus indicating again the absence of gaseous ionization.

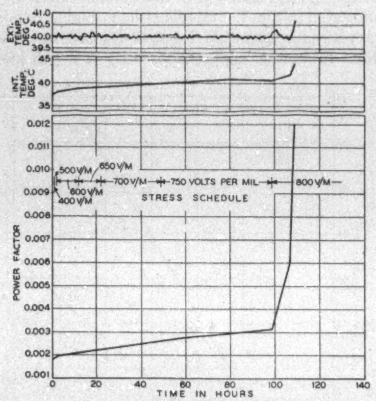

FIG. 5—POWER FACTOR—TEMPERATURE—TIME CURVES

Spec. QQ-1 Compound No. 109. Power factor measured at 180 volts per mil 40 deg C

The influence of sustained stress on power factor is seen best in Fig. 3. Some of the oils maintain their power factor fairly well up to breakdown (*e.g.*, Nos. 104, 108, and 111) while others (Nos. 109, 113) showed a uniform increase of power factor throughout relatively long lives. There is no relationship apparently between the value of power factor or its rate of increase under increasing stress, and the life of the specimen. In those specimens showing a uniform rise of power factor with increasing stress through life, this relatively slow increase is to be distinguished from the final rapid rise of power factor as failure is approached. The slow increase with stress apparently is an inherent property of the oil involving no instability. The final rapid rise of power factor evidently is the onset of instability and temperature rise in accordance with the thermal theory of breakdown.

*Differences In Life.* It is evident from Tables II and III and Fig. 3 that there are wide differences in the lives of the various groups of samples, all of which have been impregnated under identical conditions and tested in the same program, the various groups differing only as regards the oil. Looking for an explanation of these differences, it may be noted that for the most part the samples showing the shortest lives are those impregnated with compounds of relatively high viscosity, commonly used in solid cables, as for example, Nos. 100, 101, 105, and 107. In this class also is found oil No. 106 containing 25 per cent of rosin. On the other hand, 2 oils giving exceptionally long lives, Nos. 104 and 108, are both thin light oils of low viscosity. The naphthene base oils seem to fall in a group to themselves. They are characterized by a power factor increasing with increasing stress, but also by relatively long life. In a general way it may be concluded therefore, that higher viscosities tend to shorter lives and carefully refined thin oils of low viscosity may give exceptionally long lives. Further, an influence of the basic chemical character of the oils is indicated by the divergence of the naphthene group as shown later.

*Life-Capillary Properties.* In these studies it has been hoped to go much further than a mere experimental comparison of the lives of paper samples as impregnated with various oils. The chief purpose before us has been to find if possible some relation between the physical or chemical properties of the oils and the lives of samples impregnated with them. We believe that we have found an important relationship of this character in the capillary properties of the oils as related to the paper. We have found for example that the rate of rise of each one of these oils in a vertical strip of the paper obeys the well known law of the rise of a liquid in a small capillary tube. This means that it is possible to assign to each oil a definite value of "penetrative power" $K$, which is a measure of its power for penetrating the pores of the paper. The penetrative power depends on the viscosity and the surface tension of the oil, and on the effective capillary radius of the pores within the paper. The complete expression for $K$ is:

$$K = \left(\frac{r}{2}\right)^{1/2} \cdot \left(\frac{\gamma}{\eta}\right)^{1/2}$$

in which $r$ = the effective capillary radius of the paper pores, $\gamma$ = the surface tension in dynes per cm, $\eta$ = viscosity in poises. Over such a group of oils as tested here the variation in surface tension (see Table I) is much less than that of the viscosity and so the latter is by far the more important factor determining the differences in their penetrative powers.

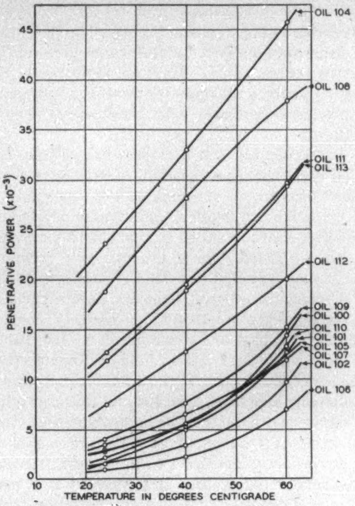

FIG. 6—PENETRATIVE POWER *vs.* TEMPERATURE VARIOUS INSULATING OILS

4 mil kraft paper

The rise of an oil in a vertical strip of paper is given by the equation $l = K \cdot t^{1/2}$, where $K$ = the penetrative power, $l$ = the height of rise in cm, and $t$ = the time in sec. A complete account of the experiments leading to the determination of the values of $K$ for each oil, its variation with temperature, the effective capillary radii of different papers, and other interesting data on capillary action have been given in a separate paper.[2] The values of $K$ at 40 deg C for each of the oils studied, as related to the 0.004 in. paper are given in column 8 of Table I. It will be seen that $K$ ranges from 2.28 for the rosin oil mixture, No. 106, up to 33 for the thin white oil, No. 104. The variation of the penetrative power with temperature for each of the oils is shown in Fig. 6.

In Figs. 7 and 8 the average life of the several samples impregnated with each oil has been plotted as related to the penetrative power. In Fig. 7 the abscissas are the values of the overall lives in hours without reference to the values of stress. In Fig. 8 the total life in each case has been reduced to 400 volts per mil by the 8th power law. As seen clearly in these figures, two definite lines or curves are indicated connecting in definite relationship the penetrative power with the life of the oil. The oils constituting the lower curve are all of naphthene base. All of the oils on the upper curve except oil No. 108 are known to be of paraffin base. No. 108 is said to be of naphthenic base but is known to have a different origin from the oils constituting the lower curve.

In order to test the interesting relationship indicated here, several auxiliary studies were made. For example, a set of samples was constructed using oil No. 105 in which, however, the temperature of impregnation and test was 70 deg C instead of 40 deg C, thereby lowering the viscosity and increasing the penetrative power markedly. The result was to more than double the life as indicated in Fig. 7. Impregnation at higher temperatures with subsequent life test at 40 deg gave no increase of life. In another case, the viscosity of a well known paraffin oil (No. 105) was lowered substantially by mixing with lighter oils. The results showed corresponding increases of life as shown by points 111 and 112, Figs. 7 and 8. Similar variations of the viscosity carried out by the refiner on the oils of the naphthene group, for the purpose of both increasing and decreasing their penetrative powers, were reflected immediately in corresponding differences in life.

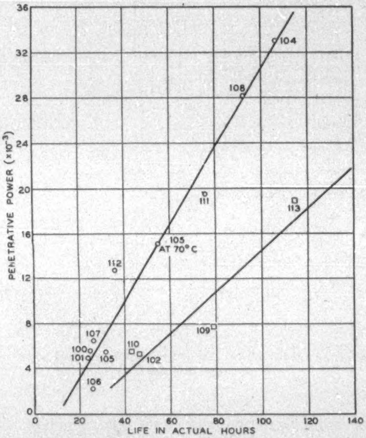

FIG. 7—PENETRATIVE POWER—LIFE CURVE

Kraft paper impregnated with various oils at 2.0 mm Hg. Life test at 40 deg C

There appears to be no doubt therefore, that in gas-free cable insulation there is a definite relationship between the capillary properties of the oil as related to the paper, and the life of the insulation under high stress. The relationship perhaps is not quite so definite as indicated in Figs. 7 and 8 because the spread of the results on each oil is not indicated. If, however, all of the life test results from Tables II and III be included, it still will be found that there is no overlap among the values giving the two curves of Figs. 7 and 8, which are based on the average values for each oil. A linear relationship is suggested in Fig. 7, but this is scarcely possible in view of the continually increasing values of electric stress. On the other hand, the upper parts of the curves in Fig. 8, based on life at 400 volts per mil, also approach fairly closely to a linear relationship. Uncontrollable variations among the specimens and the spread of test results are quite sufficient to account for the differences in the shapes of the two curves of Fig. 8.

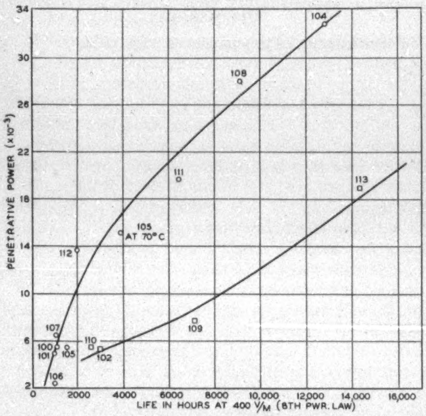

FIG. 8—PENETRATIVE POWER—LIFE CURVE

Kraft paper impregnated with various oils at 2.0 mm Hg. Life test at 40 deg C

The two separate curves for the paraffin and naphthene groups clearly suggest that the basic chemical structure of the oil also has a bearing on life. This indication is still further strengthened by the apparent identity of the law connecting penetrative power and life in two groups.

It is interesting to speculate on the particular significance of the indication of the importance of capillary penetration. It immediately suggests that failure is removed to longer periods, the more completely the paper fiber is penetrated or saturated with the oil. This picture then immediately suggests as a cause of failure some action such as ionization in the microscopic channels of the cellulose fiber. That this picture is a true one is borne out also by tests made at evacuation pressures of 0.25 mm[1] in which a noticeable increase of life was found. It seems certain therefore, that the residual air or gas remaining in the paper even below evacuation and impregnation pressures of 1 mm also plays a part in the life history. It is to be noted, however, that these residual traces of air are those existing in microscopic channels only. There is no evidence in these experiments that gaseous ionization in the original acceptance of the term, plays any serious part in the deterioration of these specimens. Gaseous ionization, if involved in the failure, is of a different and much smaller order of magnitude than that occurring in solid cables. Moreover, it is of such a character as to be subject to influence or control by the capillary forces of the oil in its penetration into the paper.

In a recent paper M. Höchstadter and W. Vogel[4] reach the conclusion that breakdown in thoroughly impregnated paper insulation is of pure electric rather than thermo-electric character. The evidence of our experiments is against this view. As indicated above, we find no serious temperature change at high stress over long periods of time, thus far bearing out the conclusions of the authors mentioned. On the other hand, we have clear evidence of approach to breakdown over several hours, during which there is a relatively rapid rise of both temperature and power factor. We conclude, therefore, that while thoroughly impregnated paper insulation may withstand extremely high stress for long periods at constant values of loss and temperature, breakdown, when it comes, is not of pure electric or other sudden type, but has all the characteristics of the so-called thermo-electric failure.

It should be emphasized again perhaps, that the results reported here pertain to a degree of impregnation and its protection which are quite unattainable under the present methods of manufacture, handling and operation of high voltage cables. Nevertheless, it has been shown that under controlled conditions impregnated paper can withstand stresses and attain life under stress far in excess of the values pertaining to the present usage of this important type of insulation. It appears a pertinent question whether it is not advisable therefore by modified methods or increased costs to take up some of this difference, not only in the oil-filled cables of the upper ranges of voltage, but also possibly in those of solid type for lower voltages.

## CONCLUSIONS

1. A series of accelerated life tests has been made on 1 grade of paper as impregnated with 14 different high grade insulating oils. Wide differences in life have been found.

2. The influence of dielectric loss on the life of impregnated paper is within wide limits, negligible as compared with other factors.

3. The values of power factor and their characteristic changes during life tests have no apparent relation to the life of well impregnated paper.

4. It is shown that the origin or basic chemical structure of the oil has an important bearing on the life of the impregnated paper.

5. Thoroughly impregnated paper will withstand electric stress far in excess of the values of practise over long periods of time without apparent change. Breakdown, when it comes, is of thermo-electric type, the approach to which may extend over several hours.

6. The differences in life in the oils of one base or origin are related directly to the capillary penetrative power of the oil into the paper. Measurements have been made of this capillary constant for each oil. For oils of one type and for a single grade of paper the life of the paper under electric stress is directly proportional approximately to the penetrative power of the oil into the paper.

### ACKNOWLEDGMENTS

This work has been carried on under the auspices and with the support of the Committee on Research of the Underground Systems Committee of the National Electric Light Association, to whom grateful acknowledgment is made. Thanks are also extended to Messrs. E. W. Greenfield, C. E. Young, and C. O. Newman, research assistants in The Johns Hopkins University, for their skillful and enthusiastic cooperation.

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## Discussion

For discussion of this paper see page 1015.

# The Effect of High Oil Pressure Upon the Electrical Strength of Cable Insulation

BY JOHN A. SCOTT*
Associate, A.I.E.E.

**Synopsis.**—*Long time overvoltage tests on oil treated cable samples and short time and impulse tests on oil treated paper sheet samples indicate that an increase in the hydrostatic pressure of the oil will result in an increase in the breakdown voltage. The magnitude of this increase depends on the time duration of the test. A doubling of breakdown voltage was secured by a pressure increase from 1 to 6 atmospheres in the case of the long time (several weeks) while no improvement at all was secured in the case of the impulse tests (several microseconds duration) by a pressure increase up to 11 atmospheres.*

## INTRODUCTION

IMPROVEMENT in cables, which combine liquid and solid dielectrics, has come largely through the study and control of gaseous electrical phenomena. This is because through circumstances of use in the field gases enter the cable structure and the resulting electrical discharges in these gas layers cause deterioration ultimately leading to failure.

The steps in improvement have led successively first to the abandonment of the heavy solids or petrolatums as treating materials and then to the oil filled cable, where the possibility of entrapped and dissolved gases is reduced to the minimum possible.

Granting, however, that some residual gas remains, its effect should be reduced if it is subjected to high pressure, for it is a well known fact that the breakdown voltage of a gas increases with the pressure almost linearly. Furthermore Koch[1] has shown that the dielectric strength of liquids shows a similar effect but that of solids does not. In order to study the combined dielectric, oil and paper, tests have, therefore, been run to investigate the effect of high oil pressures on (1) the long time or endurance dielectric strength; (2) the short time dielectric strength; and (3) the impulse voltage strength of treated paper insulation. The first two of these tests were reported to the Committee on Electrical Insulation of the Division of Engineering and Industrial Research, National Research Council, in October 1931 without publication.[5]

## LONG TIME VOLTAGE TESTS ON CABLES

Two long time or endurance voltage tests were run on actual cables. The first test was made on a 10-foot length of 2-0 single-conductor cable insulated with 0.187 in. of oil treated paper. The treating oil was a heavy cable oil of viscosity 580 seconds Saybolt at 60 deg C. Porcelain terminals were provided and oil pressure supplied by a small motor-driven pump automatically controlled to hold 80 lb per sq in. pressure above atmospheric. With the small diameter of the cable and a lead sheath thickness of 0.125 in. the lead sheath withstood this pressure without appreciable stretching during the test. A long time step-up voltage test was applied holding each step for two weeks, as shown in Table I.

TABLE I

| Kv | Average stress volts per mil | Hours |
|---|---|---|
| 75.0 | 400 | 300 |
| 85.0 | 450 | 307 |
| 93.5 | 500 | 383 |
| 103.0 | 550 | 326 |
| 112.0 | 600 | 163 |
| 121.5 | 650 | 160 |
| 131.0 | 700 | 6 |

The life at the last step was 6 hours.

Tested at atmospheric pressure the life of similar cable is of the order of 20-200 hours at 350 volts per mil. There is therefore approximately a doubling of the long time breakdown voltage when the oil pressure is increased from atmospheric pressure to a pressure of 80 lb per sq in. above atmospheric.

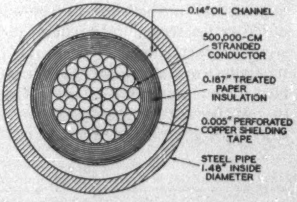
0.14" OIL CHANNEL
500,000-CM STRANDED CONDUCTOR
0.187" TREATED PAPER INSULATION
0.005" PERFORATED COPPER SHIELDING TAPE
STEEL PIPE 1.48" INSIDE DIAMETER

FIG. 1—CROSS SECTION OF 500-000-CM SINGLE-CONDUCTOR CABLE TESTED IN STEEL PIPE

Since any application of high pressure to cables in service necessarily would prevent the use of a simple lead sheath, the second test was run on a 45-foot length of cable, without lead sheath but provided with a 5-mil copper spiral shielding tape. This cable was drawn, untreated, into a length of steel pipe and provided with porcelain terminals. The physical dimensions are shown in Fig. 1.

The cable was vacuum treated after installation and filled with the oil normally used on oil filled cable. The oil had a viscosity of 100 seconds Saybolt at 100 deg F.

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*General Engg Laboratory, General Electric Co., Schenectady, N. Y.

1. For references see bibliography.

*Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26-30, 1933.*

Voltage was applied and held according to the schedule in Table II.

TABLE II

| Kv | Average stress volts per mil | Hours (held) |
|---|---|---|
| 37.5 | 200 | 25 |
| 46.7 | 250 | 53 |
| 56.1 | 300 | 24 |
| 65.5 | 350 | 42 |
| 74.8 | 400 | 168 |
| 84.1 | 450 | 168 |
| 93.5 | 500 | 165 |
| 103.0 | 550 | 165 |
| 112.0 | 600 | 165 |
| 122.0 | 650 | 225 |
| 131.0 | 700 | 192 |
| 140.0 | 750 | 1.4 |

Failure occurred at 750 volts per mil. Again the result was a dielectric strength double that to be obtained at atmospheric pressure.

## Short Time Tests on Treated Paper Sheets

The short time dielectric strength tests were made on sheets of treated cable paper, and were carried out over a range of pressures. A small pressure tank was constructed in which sheets of paper (total thickness 0.015 in.) after previous treatment in oil, could be placed and tested under pressure up to 200 lb per sq in. Tests were made between 2-in. diameter disk electrodes, with edges rounded to a 1/8 in. radius (A.S.T.M. electrodes). Two series of runs have been made so far; first, a rapidly applied test in which the voltage was raised uniformly at 0.5 kv per second until failure, and second, a minute step-up test starting at 40 per cent of the rapidly applied breakdown and increasing the voltage in 1 kv steps each held for 1 minute until failure. The results, expressed in volts per mil for these tests are given in Table III, (the values given are the averages of 10 individual tests).

TABLE III

| | Dielectric strength (volts per mil) | |
|---|---|---|
| Pressure lb/sq in. gauge | Rapidly applied voltage | Minute step-up |
| 0 | 1,280 | 970 |
| 25 | 1,600 | 1,400 |
| 55 | 1,790 | |
| 60 | 1,670 | |
| 65 | | 1,650 |
| 112 | 2,010 | 1,870 |
| 172 | 2,190 | 1,990 |

## Impulse Tests

The impulse voltage tests were made on the same type and thickness of treated paper samples, using the same electrode and equipment, as were the short time tests described above.

A (1-10) testing wave was used, *i.e.*, one which obtained its crest value in 1 microsecond and diminished to ½ crest value in 10 microseconds. The tests were conducted by starting with an impulse wave of 37.5-kv crest and increasing this value 2.5 kv between successive applications until a breakdown was indicated by a surge crest ammeter.[2,3,4] The results of these tests are shown in Table IV.

TABLE IV—IMPULSE BREAKDOWN VOLTAGE IN KV 1-10 MICROSECOND IMPULSE WAVE

| Electrode No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Average | Volts per mil |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pressure lb/sq in. gauge | | | | | | | | | | | |
| 0 | 52.5 | 55.0 | 50.0 | 47.5 | 55.0 | 50 | 52.5 | 50.0 | 47.5 | 51.0 | 3,400 |
| 30 | 50.0 | 52.5 | 47.5 | 52.5 | 52.5 | 50 | 50.0 | 47.5 | 47.5 | 50.0 | 3,340 |
| 60 | 47.5 | 50.0 | 52.5 | 52.5 | 52.5 | 52.5 | 52.5 | 47.5 | 52.5 | 51.0 | 3,400 |
| 90 | 52.5 | 55.0 | 50.0 | 45.0 | 47.5 | 52.5 | 50.0 | 55.0 | 50.0 | 50.8 | 3,380 |
| 120 | 47.5 | 47.5 | 50.0 | 50.0 | 50.0 | 50.0 | 52.5 | 52.5 | 50.0 | 50.0 | 3,340 |
| 180 | 57.5 | 52.5 | 52.5 | 52.5 | 52.5 | 55.0 | 57.5 | 52.5 | 57.5 | 54.2 | 3,620 |

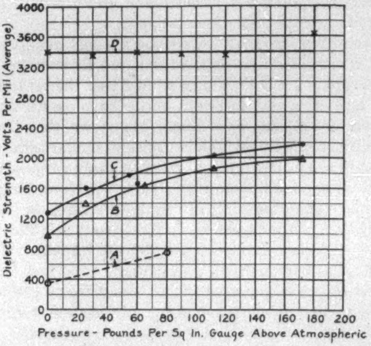

Fig. 2

*A*—Long time test on cable
*B*—Minute step-up voltage test on oil treated paper sheets
*C*—Rapidly applied voltage test on oil treated paper sheets
*D*—Impulse voltage test on oil treated paper sheets

## Conclusions

These tests indicate that at power frequencies and under long time application of voltage there is a considerable increase in endurance strength of oil treated insulation at pressures of several atmospheres. Under impulse stresses, however, practically no benefit is derived from increased pressure. The effect of pressure on dielectric strength is greater the longer the time of voltage application, being negligible for the impulse voltage tests of only a few microseconds duration and a maximum for the long time endurance test. This is shown in Fig. 2.

## ACKNOWLEDGMENT

Credit is given to Doctor G. M. J. Mackay for suggesting this work and to Messrs. J. B. Felter, J. A. Weh, B. H. Thompson and H. P. Kuehni, members of the General Engineering Laboratory staff for obtaining the data herein reported.

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## Discussion

### THE LIFE OF IMPREGNATED PAPER

(WHITEHEAD—SEE PAGE 1004)

### THE EFFECT OF HIGH OIL PRESSURE UPON THE ELECTRICAL STRENGTH OF CABLE INSULATION

(SCOTT—SEE PAGE 1013)

### ACCELERATED AGING TESTS ON HIGH VOLTAGE CABLE

(ROPER—SEE PAGE 1028)

### A NEW METHOD OF INVESTIGATING CABLE DETERIORATION

(WYATT, SPRING AND FELLOWS—SEE PAGE 1035)

**Wm. A. Del Mar:** The history of electric cables has resembled the rivalry of guns and armor plate in the Navy. As soon as a new gun or shell was developed a new armor plate was made to render it harmless, and then a newer gun or shell appeared which demolished the new armor plate and so on through many cycles. In the case of cables, higher working stresses and temperatures were the guns, ions the shells and ion-proof insulation, the armor plate.

We have seen working stresses rise from less than 40 volts per mil to 200 volts per mil, we have seen ions of water or electrolytes replaced by ions of gas, and insulation of loose lattices of low density paper interspersed with air, replaced by tight walls of high density paper, air-free, as far as the eye can detect.

This group of papers marks an epoch in the cable art because it marks a new cycle in the never-ending fight between the ion and the dielectric. Mr. Roper proves the need of removing the last trace of air, Messrs. Wyatt, Spring and Fellows show how to detect this air, and Doctor Whitehead tells us that the next step will concern the air entrapped inside the paper fibers, air not entirely removable by heat or vacuum treatment.

By clearly showing the superiority of high voltage cables having low ionization, both in service and in load cycle life tests, Mr. Roper's paper indicates that cables, which are practically gas-free behave better than those with a little residual gas. This is a very significant discovery and contrary to the general belief of a few years ago. It was then thought that a small amount of residual gas would be advantageous as a cushion to protect the lead sheath from stretching when the cable compound undergoes thermal expansion. Unfortunately, this residual air has proved to be a detriment to the life of the cable and cables had to be made which suffered their sheaths to stretch when heated and suffered vacua to form when cooled. There were two unexpected results: the operation of 66,000-volt cable had its troubles transferred from the insulation to the sheath, and vacous ionization was found to be less objectionable than normal gas ionization.

The new sheath stresses have led to intensive study of sheaths and to improvements in sheath quality. The comparative innocuousness of vacuous ionization remained to be explained. The following explanation is offered. Air films are permanent in relation to the paper and merely expand and contract in the load cycle. Vacua are not permanent but appear, disappear, and reappear in different places, each load cycle. The ionization in air films, therefore, produces accumulative deterioration of the paper, while ionization in vacua is non-accumulative and, therefore, comparatively harmless.

It would seem to be quite obvious that the value of a life test is greater, the more closely it approximates natural aging. It is not surprising, therefore, that Mr. Roper's load cycle life tests should prove to be better criteria of quality than other tests less closely related to actual operating conditions. The more closely a life test approaches natural aging, however, the more expensive it becomes and one must weigh the advantages to be gained against the cost. In the present case, the cost of the proposed tests is very high and we should be very sure of the validity of our reasons, before adopting them as specification requirements.

It would seem that an oil stability test combined with the low ionization values should serve for ordinary routine purposes, the load cycle life test being reserved for occasional check tests.

The exact nature of the oil stability test is yet to be determined. The writer does not believe that it will be an oxidation test but rather like the present Electrical Testing Laboratory test for $X$ under more carefully controlled conditions.

Messrs. Wyatt, Spring and Fellows have presented to cable workers a very valuable research tool and they are to be complimented for the completeness with which they have prepared it for use. Their paper, however, stops short of any important application of this tool and it is to be hoped that they will proceed with its application to the problems of dielectric failure.

The best starting point for research is usually where one's experimental facts do not fit one's theories. This point is found in the paper in the authors' statement that the radial hydrophil curve does not always completely explain the radial power factor curve. The power factor curve of Fig. 12 is particularly interesting because it corresponds, in a general way, with the occurrence of dendrites in a single conductor cable with thick insulation. Dendrites originate, as a rule, about one-third of the way radially from the conductor surface, the very place where Fig. 12 shows the power factor to be a maximum. Various theories have been proposed to account for this, as follows:

1. Impregnation occurs from both faces of the insulation and the inward-bound compound might be expected to meet the outward-bound compound at such a layer that the fluid resistance from it to the outside and the inside faces of the insulation would be equal. This would be somewhere within the inner half of the wall. The opposing sectors of compound would push the residual air before them with the result that there would be a concentration of air where the opposing sectors meet. This air would ionize and deterioration would start. If this theory were correct the hydrophil curve should show a decided maximum at the oil meeting layers. Apparently it does not, so that this theory may be discarded.

2. There is an energy-distance effect such as occurs in connection with corona formation around high voltage wires. A certain distance is required for ions to be accelerated by the electric field, to the speed at which they can multiply by collision and within that distance there can be no ionization.

A very considerable rise in power factor occurs, however, between the conductor and the layers of maximum power factor, indicating that these inner layers are by no means devoid of destructive activity. We may therefore dismiss this theory.

3. Under the first theory it was pointed out that the layer of maximum power factor and dendrite formation is situated about

midway of the thermal resistance of the dielectric. It can be deduced from the well known formulas that this internal midlayer also is the layer of maximum thermal resistance from the thermal sink, if we consider conductor and sheath as being jointly the sink. If, therefore, a number of hot spots forms in a cable, those nearest the layer of maximum thermal resistance from the sink will develop the greatest temperature and hence the most serious deterioration. The power factor would be raised by the charring of oil and paper, but there would be no oxidation and hence no hydrophil reaction. This theory seems to fit the limited facts available.

This discussion is not for the purpose of proving a theory but merely to indicate how the new tool might be used for researches into the origin of insulation failure.

Doctor Whitehead tries to establish a linear connection between the penetrative power of the oil and the life of cable under voltage test. While conceding that this relation exists for the higher penetrating powers, the data presented do not justify the conclusion that any such relation exists for the lower penetrating powers. Inspection of Figs. 7 and 8 rather indicates that for penetration powers under $8 \times 10^{-3}$ the life is quite independent of the penetrating power. Above $12 \times 10^{-3}$ there are 5 points on the curves which clearly indicate the linear connection claimed.

In other words, the applicability of Doctor Whitehead's conclusions to cable of the solid type is open to question, whereas he has given a very timely and important contribution to the theory of oil-filled cable.

Tests made in our Yonkers laboratory with mixtures of cylinder oil and transformer oil, indicate that there is a certain critical mixture so that with more transformer oil, the cables behave as "oil-filled" whereas with more cylinder oil, they behave as "solid." All the solid cables had approximately equal test lives. We did not determine the lives of the cables of oil-filled type, as we discontinued the life tests when satisfied that they had the ordinary oil-filled cable characteristics.

If this interpretation is correct we must suspend our judgment on the relative merits of napthene and paraffine base oils for oil-filled cables, as cable No. 113 would be deprived of support and would stand as an isolated case greatly in need of confirmation. Furthermore, we have some evidence that at higher temperatures the relative position of the two curves may be interchanged.

The drying and evacuation at such poor vacua as 2 mm of mercury, and impregnation at such low pressure as used by Doctor Whitehead, are not calculated to give ideal impregnation. The excellent life tests obtained by Doctor Whitehead with heavy oils are due probably, not so much to the thorough impregnation as to the fact that the samples are not bent before testing (as with real cables).

Doctor Whitehead tentatively explains the superiority of thin oil by its superior penetrability into the fibers. If this were so, a cable made with paper preimpregnated with thin oil, drained and reimpregnated with heavy oil, would be superior to one preimpregnated with heavy oil and reimpregnated with thin oil. Such is not the case. Furthermore, heating a heavy oil cable to the temperature at which its viscosity equals that of a thin oil should leave it equal to a thin oil cable when it cools. This is not the case. The essential feature of an oil-filled cable appears to be the use of thin oil in the tape-edge spaces.

Another pertinent fact is that an oil-filled cable even with considerable air, preserves a decided superiority over solid-type cable. Such a cable tested at a voltage sufficient to ionize the air and become very hot, will long outlast a solid type cable without developing dendrites. All of these facts are entirely consistent with the ion-reaction theory advanced.

**R. W. Atkinson:** Publication of careful original research is multiplied in value by the accurate and concise presentation of the full test procedure and results such as has been done by Doctor Whitehead. With such presentation the results can be combined with other data without necessarily following the author's formulation. Part of this discussion is to show an alternate formulation of Doctor Whitehead's data.

In the paper results are correlated by computing the life in each case at 400 volts per mil on the basis of the 8th power relation between stress and time, that is, a simple hyperbolic relation expressed by the formula $g = KT^{-n}$ ($g$ being the stress, $T$ the life and $K$ and $n$ constants). The inferred life by this calculation is many times the actual duration of the test. The reader must not assume or understand that where the calculated time is greatly different from the length of time of the test, this type of formula can be used to determine, at all closely, performance. With solid type cables, this type of formula has been found of value in comparing performances of individual samples and has been used rather freely within a time range of a few minutes to a few hours. Where cables of a given type are tested under such conditions that the total time to failure is of the same general order of magnitude for each, they may be compared effectively in this way. With cables having different voltage-time characteristics, however, the relative strength arrived at in this way is of value only for a time interval of the order used for the last voltage step, and may bear no relation whatever to the relative strength for some other time interval. For example, if we compare a given solid cable with a given oil-filled cable, we might find the one hour strength the same for both but the 100 hour strength 1.5 or 2 times as high for the oil-filled as for the other.

The ideal way to make tests so that accurate comparison is possible between different specimens is by raising the voltage at a constant geometric rate. In this way, correct comparison may be obtained between the specimens regardless of the shape of the voltage-life curve of individual samples. A modification of this procedure which is more practicable in some cases is by raising the voltage in small geometrically progressive steps at constant time intervals. Approximately with the step test, and accurately with the constantly increasing voltage, the dielectric strength of different samples is given directly for the particular rate of increase of voltage used in the tests and no calculations are required. For example, all tests made according to a program in which the voltage doubles in a given time, say 5 minutes or 5 days (by geometric increase), would be directly comparable. The writer hopes to see such a procedure to become established practice in making dielectric strength tests.

Where the voltage is increased in steps, the most accurate comparison of the tests can be made by evaluating the results so as to obtain as closely as possible the stress that will break down the samples in a time of the order of the time used in the last voltage step. By using this time interval, the error resulting from lack of accurate knowledge of the shape of the voltage-time curve is reduced to the lowest amount. It may also be shown mathematically that errors resulting from averaging tests evaluated in this way are much less than those produced by averaging tests evaluated in terms of time.

Consideration may be given here as to the voltage-time characteristics that may be obtained on samples such as those tested by Doctor Whitehead. Figure 1 shows the results of tests made in our laboratory to compare the electrical behavior of various oils by means of breakdown data on short cable samples all cut from the same length of dry core and impregnated in the desired oils in sets of 6 or 8 or more samples. The samples comprising a set were stripped to different thicknesses of insulation, the entire set being submitted to the same voltage, thus each sample being tested at a different stress, each being tested until failure. We were thus enabled to construct the stress-life curve for each kind of oil in the time range between a few minutes and 500 hours. It will be noted that in all cases except one, the curves when drawn on log-log paper with life as abscissa and stress as ordinate are concave upward, which means that a simple hyperbolic relation does not express the characteristics for any wide time range. For a short time range such relation can be used satisfactorily, the exponents being found here to range between 35 and 100 (except for the one case) in the vicinity of 10 hours life. In view of the character of our samples and those of Doctor Whitehead and in the absence of other specific data, we are inclined to believe that for Doctor Whitehead's samples the exponent would fall in the same range.

We have therefore recalculated and replotted Doctor Whitehead's data in terms of dielectric strength versus penetrating power, (see Fig. 2). Two sets of curves are given, one plotted on the basis of the 80th power and one on the basis of the 20th power, the time in each case being 10 hours. The maximum difference between strengths evaluated in these two ways is 5 per cent, and it will be noted that a satisfactory comparison is obtained between the two types of oil by using either exponent. A satisfactory comparison also would be obtained if the 8th power were used. It should be pointed out, however, that due to the different average time at the last step for the samples with lower strength than those with higher strength, the upper part of each curve is not directly comparable with the lower part and no method of comparison of these samples can be precise without knowledge of the shape of the voltage-time curve for these samples.

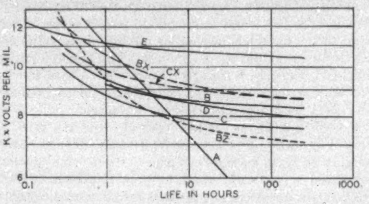

Fig. 1

Only a synopsis can be given here of the reasons for the greater accuracy with which such data can be compared on the basis of voltage for a given time rather than time for a given voltage. It should be understood, however, that the voltage evaluation not only is more accurate than the other, especially where the voltage-time characteristics are not known accurately, but also gives a direct and concrete interpretation of the test data rather than an abstract mathematical statement.

Mr. Wyatt has presented several new tools that should be very useful. To illustrate the importance of the method of measuring dielectric loss tape by tape, the writer refers to the fact that we have frequently measured the loss of the entire thickness of the dielectric and have then measured successively portions remaining after outer layers have been removed. This incomparably is less accurate and permits the division of the dielectric into three or four parts at the most. To have developed the very simple and rapid procedure described and to have shown it to be accurate and reproducible is a very valuable accomplishment.

The subject of effect of hydrostatic pressure on the dielectric strength of oil-saturated paper reported upon by Mr. Scott is due to receive more attention both for its direct application and for its aid in the theory of dielectric behavior. Mr. D. M. Simmons and the writer presented some data of this kind in 1931.[1] This was given in connection with the description of condenser joints and had reference to the dielectric strength parallel to the surface of the paper, which is an important item in jointing and terminating of cable. As might be expected, the effect of pressure is numerically different under these conditions than perpendicularly to the surface of the paper as in Mr. Scott's tests. In our tests no indication was found of variation of strength with variation of time of application of voltage within the limits of one second to 30 minutes. The effect of pressure was to increase the breakdown strength as something like the 1/8th power of the absolute pressure in the range of pressure used. In comparison, Mr. Scott's results on tests normal to the paper layers, showed for the longer test intervals, doubling of the strength for the pressure increase from 1 to 6 atmospheres. This corresponds to a gain in strength of something like the 0.4 power of the absolute pressure. We also observed that the "spread" of results for different samples tended to become smaller as the pressure was increased and that the stress became decidedly smaller as the space between electrodes was increased. All of this is in line with Mr. Scott's suggestion that occluded gaseous films explain the variation in strength with pressure.

**W. F. Davidson:** Mr. Roper's paper deals with methods applicable to complete cables. The method of accelerated aging tests seems to be particularly effective and it is to be hoped that further work will be done along the same line with cables of other types. The results so far obtained are very helpful in evaluating the effectiveness on acceptance tests of new cable and appear to be helpful as a type test in connection with the rating of cable of new designs or construction.

Messrs. Wyatt, Spring, and Fellows have approached the general problem from an entirely different angle; namely, that of finding out just what is happening in the various parts of the cable. They have gone along an entirely new path and the reports of their reconnaissance are most encouraging. We are now in a position to add some quantitative measurements in a field where previously it has been possible to do only the crudest type of qualitative work. Through the methods described we appear to be well on the way to a more complete understanding of just what is happening in a cable as it deteriorates. With this information, it will be possible to approach the cable design problem and make a more intelligent attack directed toward eliminating deterioration. The writer commends the methods to other investigators and urges that they apply them to a wide range of cable types and conditions.

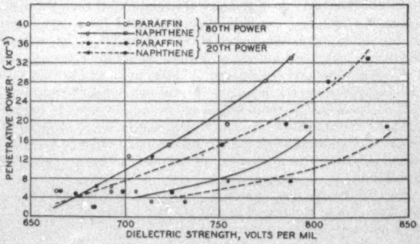

Fig. 2

**Herman Halperin:** As the thicknesses of insulation in underground cables are reduced, the problem of having ample impulse strength becomes increasingly important. For example, for 66-kv cables of the ordinary type, the impulse strength of the insulation is now about 4 times the maximum surge voltage that may occur incidental to switching. However, as indicated by Mr. Scott's work and other data, increasing the long-time strength of insulation by the use of pressure or of the oil-filled principle and thereby reducing the required insulation thickness by 50 per cent means the ratio of impulse strength to operating surge voltages is reduced from 4 to 2, or less. Probably this ratio of 2 is satisfactory, but nevertheless the situation indicates a limit on reductions of present types of insulation, unless changes are made in switching arrangements.

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[1] *Oil Filled Cable and Accessories* by R. W. Atkinson and D. M. Simmons, Trans. A.I.E.E., Dec. 1931, p. 1421.

As the writer has information indicating a unit impulse strength of insulation in cables of about 30 per cent less than the value obtained by Mr. Scott on a few flat sheets of impregnated paper, it would be interesting to learn if he has correlated his results with impulse tests on cables.

Doctor Whitehead's valuable article would still be more interesting if he had made tests on effects of various oils in samples impregnated similar to the so-called solid type cables.

Regarding his statement that "no compound of outstanding resistance to ionization has been found," tests on compounds and on completed cables, and operating experience indicate that there has been in many cases a very large improvement in this resistance characteristic of compounds used in the past 10 years.

In view of his statement that the penetrative power of oil and the life of the impregnated paper insulation increase with the square root of the effective capillary radius of the paper, it might be concluded that the life of impregnated paper insulation in cables would be higher with low density paper than with high density paper. On the other hand, in recent years there has been a tendency to use high density paper particularly adjacent to the conductor. The limited data received by us in short and long time high voltage tests indicate that the unit breakdown strength is increased slightly by the use of the higher density paper.

In the manufacture of cables of the ordinary type, there has been a distinct tendency during the past 8 years toward the use of less viscous compounds, which is in agreement with the results of Doctor Whitehead's research.

In connection with conclusion 4, further research on the effect of the chemical structure of the oil on the life of impregnated insulation would be of interest.

The methods of test described by Messrs. Wyatt, Spring and Fellows are very valuable because examination of dissected cable insulation has shown in all cases the deterioration, if any, in the insulation is very irregular across the radius of the cable. Tests on the cable as a whole do not give the detailed picture that these new methods will give. The Commonwealth Edison Company is constructing an apparatus for measuring the power factor of several small portions of individual tapes.

It would be of interest to know the relation between the average power factor of the individual tapes and the power factor of the cable insulation before it was dissected. The authors report that they used a stress of 50 volts per mil in the tests on the individual tapes and the writer would like to know whether, with this high stress in tests in air, there were any signs of ionization.

The discussion of the possible sources of entrance of oxygen to cause the localized regions of high hydrophils is interesting, but it appears that more work is necessary in order to establish more definitely the mechanism of entrance of oxygen into the insulation.

Fig. 9 indicates that there is no consistent relation between the amount of wax in insulation and the percentage of hydrophils. This lack of correlation seems reasonable, as wax formation is a polymerization process while hydrophil formation is an oxidation process. However, wax formation still is considered undesirable in cable insulation because of the increase in ionization which accompanies it. Therefore, while conclusion 2—that oxidation is a major cause of deterioration of solid type cables in service—is true, it should not be concluded that oxidation has replaced ionization and polymerization as the major cause of failure in high voltage cables of the ordinary type.

Regarding conclusion 4, that ionization, as indicated by wax deposits, does not appear to cause sharp increases in dielectric losses, we have found that with 66-kv cables that have deteriorated in service or in accelerated aging tests the increase in ionization loss is considerable in many cases; that is, increases of one-half to one and a quarter per cent in power factor have been found. In most cases, the increase in so-called solid loss was less than the increase in ionization loss at room temperature, while the reverse was true at elevated temperatures.

It is stated in the paper that the viscosity of the oil was found to vary across the radius of the cable. How were these viscosities determined?

**F. M. Clark:** With reference to Doctor Whitehead's paper the writer is particularly pleased to report substantial agreement based on the work done at Pittsfield. Some 4 or 5 years ago, we realized the necessity of investigating those factors that were fundamental in the manufacture and use of mineral oil as a dielectric, especially for use as an impregnant of fibrous insulation. Although our scheme of attack was quite different from that which Doctor Whitehead has followed, our conclusions in the main are substantially the same. For instance, we observed that a considerable variation in the life of oil-impregnated paper was obtained when no other factor than the type of impregnating oil was changed. This agrees with Doctor Whitehead's conclusion 1. The life of our impregnated papers seems to bear no relation to the dielectric loss either initially or as estimated by power factor values during the life test. This agrees with Doctor Whitehead's conclusions 2 and 3. Doctor Whitehead has further concluded that the origin of the oil is of significance in determining the life of the impregnated paper. We agree.

It is with conclusions 5 and 6 that our research work varies somewhat in nature from Doctor Whitehead's scheme of attack, although here again we reached somewhat the same conclusions. We observed in our work, which we hope to present in the near future, that in every case of insulation failure on life test clear evidence of gas elimination in the period immediately preceding failure was obtained. This did not necessarily result in the so-called wax formation. Our conclusion was that in the type of breakdown with which we were dealing, at least, gases were eliminated from the oil because of phenomena which we desire to discuss in future publications, the details of which space does not allow us to present at this time. With this gas elimination, ionization and dielectric failure soon resulted. It may be that this gas elimination was of a thermoelectric origin somewhat in the manner that Doctor Whitehead suggests. There is, however, some evidence that the cause of gas elimination is not strictly a thermoelectric phenomena.

Doctor Whitehead, as a result of his work, emphasizes the importance of the capillary constant. In our work we emphasize the chemical constitution of the oil. It may be that an oil meeting the chemical tests which we have set up would possess high penetrative powers. If so, our work would again be in complete agreement with Doctor Whitehead's.

However, has Doctor Whitehead determined whether the capillary constant for different oils would be affected if it were determined under a vacuum rather than in contact with air? Also, has Doctor Whitehead determined if an oil having highly favorable "penetrative power" with wood pulp paper possesses the same favorable characteristics with other grades of paper such as linen or cotton?

Doctor Whitehead probably is correct in stating that the "specifications for a cable oil are limited usually to values of low voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity . . ." He will be interested to know, however, that as a result of the researches which we have completed, our insulating oils, including cable oils, are inspected closely for their paper-impregnation characteristics and the stability of the resulting impregnated paper under voltage at a higher than room temperature ambient.

It is observed that the life tests described in Doctor Whitehead's paper are carried out in contact with air. The writer asks if any data are at hand which would lead to similar conclusions as those enumerated if life tests were carried out in the absence of air (simulating cable practice).

**Robert J. Wiseman:** Heretofore, we have been concerned with the kinds of paper or oil we should use, how they affect the physical and electrical characteristics, such as tensile strength, folding endurance, dielectric strength and dielectric loss. Tests reported by utilities, testing laboratories such as the Electrical Testing Laboratory and the manufacturers have shown a steady improvement up to a few years ago and then very little change. With the better understanding of cable characteristics, a more intelligent manner of operation took place and although the utilities attempted to get all the power load possible out of a cable, they did not desire to do so and at the same time, sacrifice operating efficiency. A study of operating records indicated that failures in service when classified were about 20 per cent attributable to inherent causes. To reduce these, it was necessary to go further than the tests made at the factory or the acceptance tests on installation to find out why cables failed. This introduced the so-called accelerated aging tests. It is not new. It has been used for many years, at least 15 years in England. So far it is still in the early stages of application in this country. Mr. Roper has very clearly outlined the development stages passed through to improve impregnated paper cables, and finally why he arrived at an accelerated aging test. Mr. Roper refers to the change from greases to heavy oils as the reason for improvement in dielectric strength. The writer believes it is not only the change to heavy oils, but also the introduction of wood pulp paper of fairly high air resistance in place of manila hemp paper which everyone now knows is not satisfactory. Here again, we have introduced English practice.

Since 1926 the quality of oils and papers has greatly improved. The encouragement given in Mr. Roper's paper is shown in the various plots where he compares the voltage-time, power factor tests, and ionization factors for cables manufactured from 1926 to date. The quality of 66-kv cables has greatly improved and it is wished that Mr. Roper could have made his accelerated aging tests on cables of a later vintage than 1926 where in all probability he would have obtained even better results than he obtained on the 1926 cables and have even more faith in the value of these tests.

The curves showing the improvement in power factor and ionization factor with year of manufacture are particularly significant, in that, even in the short time of 7 years, a big advance has taken place in the quality of the insulation furnished.

As a result of aging tests made by some of us and reported to other meetings of cable engineers it appears that we shall go even further than heretofore in using still thinner mineral oils, particularly for the higher voltage cables, such as Mr. Roper has reported. This becomes necessary if we are to continue using solid type cables for 66-kv and obtain the long life expected.

With the improved quality of insulation which the cable manufacturers are furnishing today by reason of improved processes of manufacture and better materials—paper and oil—a new nightmare has arisen to confront the cable manufacturers, namely, the increasing number of cable failures due to lead sheaths. Mr. Roper calls them "lead sheath troubles." The writer likes to view them as operating troubles. In our desire to improve the quality of our cables we did not pay as much attention as we should to the lead sheath, devoting our time to improved insulation, so that the insulation research went ahead faster than the lead research. We use lead as the protective covering—a low tensile strength, ductile material has no yield point, and with constant stress, will stretch. In our cables we now have so much oil and almost an absence of voids that with the heating up of the cable, the oil expands and produces extremely high internal pressures—as much as 115 lb per square inch at the conductor and 80 lb per square inch at the sheath. The lead cannot withstand this pressure and will expand. Repeated load cycles with migration of oil from the joints into the cable causes cumulative expansion, the sheath splits, oil drains out and the cable fails. If the deterioration of the insulation is not given as the reason for the failure, the lead is condemned as defective. Actually the lead sheath originally was too thin and not able to withstand the internal pressure. The cause of failure is assignable to operation and not to quality of cable. We are now realizing that lead has its physical limitations and the recommendation to increase the thickness of lead sheaths for the larger diameter cables should be emphasized. We never hear of lead sheath troubles for small diameters such as 1 to 2 in., but 2.5 in. and over. The story Mr. Roper refers to could not be written or told if we had increased lead walls.

Doctor Whitehead seems to have drawn upon all his studies to state his conclusions. His results give us an inkling as to what we should get eventually for paper impregnated insulation. However, we must not hope for too much from some of the oils which he indicates are superior to others. His tests are made under ideal control conditions which must be so, if we want to classify oils properly, but the final answer will come when we make up cable and then conduct accelerated aging tests on it such as Mr. Roper has done or some other way, in order to introduce all influencing factors. The conclusions of Doctor Whitehead are due to his manner of testing.

Doctor Whitehead's samples are metal rods carefully hand wrapped, perfect control for drying and impregnating, no chance of bending to upset the position of the papers and as they have a very thin wall, he does not get the gradation in saturation likely to occur for heavy walls. Also, he did not make temperature cycle tests to affect the uniformity of impregnation. If we always keep in mind that he refers to well impregnated paper, he is correct, but in our ordinary type of cables, this exists for only a few load cycles. Therefore, dielectric loss, power factor, and its changes as noted by ionization are big influencing factors on the life of cables.

Doctor Whitehead reports that he found no wax in his samples, but did find gas. We believe if he had continued his tests at the lower voltages and, therefore, for a long time, wax would have formed in the time period between the generation of gas and breakdown. A much longer time of test is needed than was used by Doctor Whitehead to find out if the oils will wax.

Roughly, Doctor Whitehead confirms the belief of some of us that the lighter oils are preferable to high viscosity oils for high electric stressed cables and as we get to know more about them, there will be an increasing tendency to use them.

Years ago, when we did very little time-voltage testing, rather rising voltage tests, the writer could not appreciate thermo-electric theory, believing it to be a pure electric ionization phenomenon. Today, with all of our tests, whether on rubber, varnished cambric or paper—a voltage-time test, the writer still believes it is an ionization phenomenon but thermo effects result, changing the original electrical character of the dielectric, giving the appearance of a thermo effect only. It is doubted that there can be breakdown due to heating by voltage without considerable ionization.

The paper by Mr. Wyatt and his associates describes a new tool for aging tests. It seems as if it is an adjunct to our present accelerated aging test method, in that, with our long lengths and load cycles, we study the uniformity of the insulation longitudinally and finally get failure at the weak spot. After we have completed the current-voltage-time test we can take the author's test for hydrophil number and power factor of the insulation and note how they have changed as compared to the cable when new. This will be a measure of how the cable deteriorates radially. It will be necessary to gather considerable data from both test methods in order to correlate them so that we do not overemphasize what a high hydrophil number indicates nor how the power factor changes, *i. e.*, how shall we interpret a wide range in hydrophil number or wide changes in the power factor across the insulation with the expected life in the cable.

Mr. Scott's paper is of particular interest. Nearly 3 years ago when we were conducting our first accelerated aging tests, we noted the migration of the oil in the insulation leaving voids within the latter and not next to the conductor or the sheath. We also noted the high pressures that are developed when the load is thrown on (115 lb per square inch in 15 minutes) and how quickly again a vacuum will be created (20 in. in half hour) when the load is taken off. Neither the pressure nor the vacuum are beneficial to the cable and, therefore, should be eliminated. Also we did not like the abuse the lead sheath received due both to pressure and vacuum. Why not get rid of both effects. Put the cables without lead into a pipe, fill the pipe with oil and lead troubles are eliminated. By putting on a high pressure, you will never create voids and any further increase in pressure can be taken care of. Mr. Scott confirms some of our own studies on the improvement in dielectric strength of insulation. We have gone further and carried out elaborate accelerated aging tests in our laboratories on high oil-pressure cables in steel pipes, combining current and overvoltage, and demonstrated most satisfactorily that here lies the future high voltage cable, as it has thermal and electrical characteristics far superior to both solid and oil-filled cables and at the same time, simplifies the installation of a cable system with a minimum amount of maintenance.

**Hubert H. Race:** I was particularly pleased with Doctor Whitehead's conclusions (5) and (6) because our experience also indicates that electrical failure of oil impregnated paper normally is thermoelectric in character. We feel that breakdown is preceded by ionization in a gas phase. In cables this ionization may occur in residual air, $CO_2$ or water driven out of solution by changes in temperature and pressure or even in vapors of light fractions of the oil itself if local temperatures are high enough and gas pressures low enough. For this reason the ability of the oil to wet the paper fibers is very important since the smaller the attraction of the oil for the cellulose, the easier the formation of a gas layer at the oil-cellulose interface. This wetting ability directly is related to "penetrative power" measured by Doctor Whitehead although the surface tension measurements give oil-air rather than oil-cellulose interfacial tensions. About 2 years ago, we tried to find a convenient means for measuring oil-cellulose interfacial tensions, but with little success. However, we feel that hydrophil content of an oil is a measure of the constituents which would have an affinity for paper and would, therefore, give wetting properties. If Doctor Whitehead still has unoxidized portions of the oils used in his investigations it might be very interesting to compare their hydrophil content with the other properties that he measured.

In discussing the paper by Mr. Scott the major advantage of high pressure cable is that it may be possible to increase operating voltage gradients in the oil-paper insulation. There is one disadvantage, however, which cannot be overlooked and that is the fact that the dielectric loss per unit volume of the insulation increases as the square of the voltage gradient. In the 132-kv oil filled cables, the dielectric loss already is an appreciable percentage of the allowable copper loss as shown by case (1) of the accompanying table. For comparison, rough calculations have been made for the following assumptions involving doubled voltage gradient. In case (2) the same physical dimensions have been retained, but the operating voltage is doubled. In case (3) the same operating voltage has been retained, but the thickness of the insulation has been reduced so that the gradient is doubled. The same total watts loss per foot of cable in each case has been assumed.

TABLE I—COMPARISON OF LOSSES AT DOUBLE GRADIENT

| | (1) | (2) | (3) |
|---|---|---|---|
| Dielectric loss (watts per ft) | 1.02 | 4.08 | 1.8 |
| Copper loss (watts per ft) | 7.12 | 4.06 | 6.34 |
| Total loss (watts per ft) | 8.14 | 8.14 | 8.14 |
| Allowable current (%$I_1$) | 100.00 | 76.00 | 94.00 |

Both of these assumed conditions show that the dielectric loss is far from being negligible, in fact in case (2) it becomes equal to the copper loss so that the current must be reduced to 76 per cent of case (1) in order to prevent overheating. This brief survey indicates that if higher electrical gradients are to be used in cables, either the current carrying capacity must be reduced or higher operating temperatures must be allowed, or the oil impregnated paper must be improved so as to decrease its power factor.

Messrs. Wyatt, Spring and Fellows should be congratulated upon the development of tools for measuring electrical and physical properties of dissected cable layer by layer. We have done considerable work on the power factor and hydrophil content of cable oils under different conditions and our results agree in general with the conclusions stated in this paper for actual cable samples. There are several detailed comments made in the following:

1. It might be possible to develop another tool for use in this layer by layer study, namely, the analysis of gases absorbed in the oil in different layers of a cable. Some form of hollow steel needle could be inserted axially between layers of a freshly cut cable section, and a small portion of oil could be drawn into an evacuated chamber and the gas so liberated could then be analyzed. A rough estimate indicates that if the oil contains 1 per cent of gas by volume, 0.1 cc of oil would be the minimum quantity from which to obtain gas enough to be analyzed by microanalysis. By improving existing methods and using both McLeod and Hale-Peroni gages for gas pressure measurements, it might even be possible to determine the water content of oil in cable in this manner. The authors state that there is need for such determinations and that no method is now available.

2. The author's explanation of so-called *U* curves of hydrophil content and power factor plotted against radial thickness of insulation seems to be that oxygen migrates along the core and sheath and thence radially through the insulation so that the maximum amount of oxygen and, therefore, the maximum change occurs in the layers of paper nearest the core and sheath. This is certainly a possibility and perhaps a probable explanation, but there is a further thought. Even though the oxygen distribution were uniform throughout the volume of the insulation, the catalytic action of copper and lead would result in a concentration with time of oxidation products in the oil nearest the core and sheath.

3. The authors observed that "most of the oxidation products are concentrated in the oil within the paper tape rather than in the excess interlayer oil on the outside of the tapes." It appears to the writer that the rather obvious reason is that these products are polar and are attracted definitely to and become adsorbed on the paper fibers. This very property makes them valuable from the standpoint of electrical endurance.

4. The authors report hydrophil content in per cent. This practice seems very questionable because it involves arbitrary assumptions as to both the cross sectional area and the molecular weight of the molecules that have an affinity for water. In a complicated hydrocarbon mixture like mineral oil, the hydrophilic molecules may vary widely in section and weight so that only average values are determinable at best. Instead of making arbitrary average assumptions for these two quantities, it seems much better to report hydrophil content as sq cm area of film per gram of oil, which gives the actual area of spread per unit quantity independent of molecular size or weight.

**D. W. Roper:** Doctor Whitehead says: "for increased current capacities, higher voltages, and higher temperatures, the oil-filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely."

There was installed recently in Chicago a 66-kv single conductor line of underground cable having a carrying capacity of 100,000 kva as the summer rating. This cable had the so-called "solid" type of insulation because its cost installed was 10 per cent less than a line of oil-filled cable of the same capacity. The oil-filled cable of itself costs less than cable with the solid type of insulation, but the cost of stop joints and oil reservoirs still is so high that with the increased labor cost of installing the oil-filled cable, these items more than offset lower cost of the cable itself. In spite of the fact that the prices of nearly everything else on the market have been reduced in the past 4 years, the price of these oil reservoirs has shown an upward trend.

In order to get the benefit of the higher permissible operating temperature of oil-filled cable, either the cable must be installed in separate conduits, or other cables in the same conduit must be derated to prevent their maximum temperature exceeding safe limits. These latter conditions will remain, even if the oil reservoirs and stop joints are reduced in price. These commercial considerations indicate the desirability of continuing the studies on the solid type of insulation with a view to its further improvement and reduction in its cost.

At the time that Doctor Whitehead's life tests were started, the accelerated life test, that is, the continuous application of voltage several times normal, was the best known method for the purpose. As he states, his samples have a degree of impregnation quite unattainable in commercial practice and the stresses during test range from 7 to about 12 times the maximum stresses used in commercial practice. Recent investigations indicate that a lower maximum voltage continuously applied, with load cycles, gives results that correspond more nearly with the service experience and, further, that the relative stability of various types of insulation under such accelerated aging tests is a more valuable method of comparing different types of insulation than their life at constant temperature.

**Kenneth S. Wyatt:** Doctor Whitehead has succeeded in sufficiently controlling the many variables so as to bring order out of chaos and establish a definite relationship. The dependency of life upon the penetrativity of the compound, together with the method for determining penetrativity, constitute a valuable contribution which cannot help but influence practice.

In the introduction, the inference is made that the breakdown studies find application in oil-filled cable operation. Such an inference appears doubtful for three reasons: First, breakdown is not a problem in oil-filled cable operation since ionization has been practically eliminated; any reasonably good insulating oil of correct viscosity would probably be entirely satisfactory as far as breakdown is concerned; only when the insulation thicknesses are reduced would breakdown characteristics become important, and even now tests have been reported where the insulation has been reduced nearly 50 per cent without any sign of breakdown troubles. Secondly, oil-filled cables are fairly thoroughly degassed, whereas it is probable that Doctor Whitehead's samples contained dissolved gas. The breakdown characteristics of oils are influenced to a great extent by their dissolved gas content, and Doctor Whitehead himself has shown that the life of oil-impregnated paper insulation is greatly influenced by residual gases. Although the samples were degassed at time of impregnation, they were placed in a bath of oil exposed to the atmosphere. F. M. Clark has shown (*Jl. Franklin Inst.*, Jan., 1933) that air diffuses very rapidly into shallow baths of oil; his results undoubtedly were influenced considerably by convection currents, and it is probable that the same factor would operate to dissolve gas in the oil to a much greater extent in the case of Doctor Whitehead's experiments where a pronounced temperature difference obtained (40 deg to 80 deg C oil and air at room temperature). Perhaps we can assume that the oil bath in which the samples were submerged was air-saturated; the degree of air-saturation of the insulation under test would then depend on the amount of gas diffusion through the holes in the inner and outer electrodes and at the guard ends. Thirdly, is it not probable that at such exceedingly high stresses as 500, 600, and 700 volts per mil phenomena occur which do not enter into consideration at operating stresses of 100-150 volts per mil? For instance, it has been suggested that a secondary ionization occurs in the gas films condensed along the fiber surfaces; such secondary ionization might only occur at very high stresses, say 600 volts per mil or over, although at 200 volts per mil it would not be a factor. Some such effect may be indicated by the curves of Fig. 3. The increases of power factor with voltage of oil 102 may not represent an accelerated effect, but may indicate an aging that is entirely absent at lower stresses. The point of this discussion is that there is considerable question about applying many of these breakdown results to operating cables. The work described has evidently been well directed and carried out; we appreciate that researches of this type are essential to feed the more practical studies, but believe that at present it is unwise to attempt to interpret these results so as to make them directly applicable to practice.

Fig. 3 shows a continual increase in power factor with hours of aging for several of the naphthene base oils. May this not be due to oxidation or oxidation in the presence of ionization? The initial values of power factor for these oils are higher than the other oils, indicating perhaps that they contain unsaturates which have combined with oxygen since the refining process. The longer life of these oils might be explained as due to the presence in the oils of unsaturates according to the following speculative theory: Most theories of breakdown hold that cumulative ionization takes place in the gas phase in some stage of the failure. Those oils that evolve large quantities of gas when subjected to ionization should tend to fail more readily than those oils evolving smaller amounts of gas. Our studies of the effect of structure on gas-evolving properties of oils under cathode ray bombardment indicate that the greater the unsaturation, the less the gas evolved. It would be interesting to learn whether Doctor Whitehead's longer-lived oils contained any appreciable amount of unsaturates that would take up gas liberated by ionization from the more saturated portions of the oil. It is unfortunate that no data are available as to the probable structure of these oils; even iodine and sulphuric acid values would give some idea of the content of unsaturates.

In the study of the effect of structure on breakdown it would be highly desirable to work with synthetic oils typical of several classes of structure. The methods by which these oils may be produced have only recently been developed. One advantage of these oils is that they may be obtained pure and free from the sulphur that is present in most natural oils even after refining. It must, of course, be realized that even when structure has been related to electrical breakdown it may be difficult to select satisfactory natural oils for service unless we have means of determining their structure.

Although it is true that considerable effort has been expended in studying wax formation and allied phenomena referred to in the introduction, usually such studies have formed only a part of general cable investigations. Doctor Whitehead finds little encouragement in the results of wax studies in producing new or improved types of cable. However, it should be emphasized that many of the ionization studies have had as their object not only the selection of resistant materials but of learning more of the nature of ionization and the mechanism of the changes which it causes in oils and papers. Solid type cable will hold its place for high voltage transmission up to 66 kilovolts for a long time to come; hence a clear understanding of the deterioration processes is essential to improved operation. Not all are as sure that oil-filled cable is the complete answer as is Doctor Whitehead. It is common experience in making improvements that when one trouble is suppressed another may become more pronounced.

In conclusion, the problems of high tension insulation are so involved that it will only be by attacking them along a number of different lines that a complete solution will be obtained. It is of the highest importance to the industry in general that these researches be sustained. One of the most vital of such researches is Doctor Whitehead's undertaking; it is greatly to be desired that funds will be forthcoming for its continuance.

**H. A. Dambly:** Mr. Roper concludes that loading is one of the important factors effecting the stability of cable insulation, and points to the necessity for including actual loading cycles combined with voltage tests if long-time performance of the insulation is to be predicted. He supports this conclusion by citing operating experience with heavily and lightly loaded lines.

Operating experience with the 66-kv cables of the Philadelphia Electric Company supports the view expressed in regard to the importance of loading. The following table shows the record of failures attributed to insulation defects or deterioration for three installations. Each consists of single conductor 750,000 cir mil cables of the so-called solid type, the first (6601-6602) having 938 mils of insulation (30/32in.) and the others 812 mils (26/32 in.). Interpretation of the performance of these lines is clouded by the fact that in addition to the 31 failures listed there were 23 of which the cause could not be assigned.

66-KV CABLE—INSULATION FAILURES ASSIGNED TO MANUFACTURING DEFECTS OR DETERIORATION

| Line No. | Service date | Loading Conditions |  | Failures—by years |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Rating kva | Max. sustained kva | 1926 | 1927 | 1928 | 1929 | 1930 | 1931 | 1932 | Total |
| 6601<br>Mfr. X—11.26 mi | March<br>1926 | 50,000 | 35,000<br>Since 1930<br>30,000 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 2 |
| 6602<br>Mfr. W— 3.75 mi | March<br>1926 | 50,000 | 35,000<br>Since 1930<br>30,000 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 8 |
| Y— 7.50 mi |  |  |  | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 6603<br>Mfr. Y—19.39 mi | October<br>1926 | 50,000 | 50,000 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 |
| 6621<br>Mfr. W—16.37 mi | October<br>1926 | 60,000 | 60,000 | 3 | 7 | 0 | 1 | 0 | 0 | 2 | 13 |
| 6604<br>Mfr. Y—19.39 mi | August<br>1927 | 60,000 | 50,000 |  | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| 6622<br>Mfr. X—10.89 mi | August<br>1927 | 60,000 | 60,000 |  | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Z— 5.48 mi |  |  |  |  | 0 | 0 | 0 | 0 | 0 | 1 | 1 |

NOTE: In addition, there were 23 failures for which the cause was not assigned.

Eliminating the failures which occurred in 1926 and 1927, due to initially defective insulation, and recognizing that there were a large number of failures due to unknown causes, it still seems significant that on the 2 heavily loaded installations (6603-6621, and 6604-6622) 9 failures occurred in 1932 that were attributed to insulation deterioration, while on the lightly loaded installation (6601-6602) there have been no failures attributed to insulation defects since January 1928. Experience thus far in 1933 continues that of 1932.

While it is unsafe to generalize too freely in comparing the records of several systems, due to differences in maintenance practices and other variables, the relative effect of loading on the performance of the Philadelphia cables is similar to that in Chicago.

**J. B. Whitehead:** In the paper by Mr. Roper we have for the first time a correlation between service record and accelerated life tests in cables. There is nothing surprising in the correlation that has been found. Accumulated evidence from various directions is almost overwhelming that the failure of solid cables in service is due to internal ionization super-induced by temperature cycles. Consequently approximate and intensified service conditions applying to the laboratory must necessarily give similar results. The only question that has existed as to the value of the accelerated life test has been whether or not the short time and the higher voltages have introduced factors not present in service. The present paper shows the limits of acceleration within which agreement is to be found and even suggests that a higher rate might probably be utilized.

The results reported indicate wide differences in the values of ionization factors. Several examples are shown of a decrease of ionization factor with time (see Fig. 11). This is the most interesting question presented by this paper. The present accepted theory of gaseous ionization as the result of temperature cycles seems to call for an increase in ionization factor in all cables of this type. What then are the differences amongst the cables here reported which give such wide variation amongst the values of ionization factor?

It is the understanding that Mr. Roper is proposing tests of this character for the predetermination of cable quality. Two or three weeks are mentioned as the possible time over which they might extend. Is he not unduly optimistic as to the moderate additional cost which is involved? Looking at the other side of the picture one may well ask whether it might not be worth while to compare these costs as well as the performance characteristics for solid core cables with the corresponding cost and behavior of the oil-filled cable. The writer's suggestion is that the excess first cost of the oil-filled cable may be lowered substantially if in the interest of satisfactory life, it becomes necessary to burden the solid cable with an elaborate program of preliminary accelerated life tests.

The two instruments described in the paper by Messrs. Wyatt, Spring and Fellows constitute important new methods for studying the changes which take place in impregnated paper insulation in service. At first sight it might appear that since small differences in oxidation production are being measured, the well known avidity of cable oils for the absorption of gases might well lead to error in the open methods used for both power factor and hydrophil content. However, the variations which have been found as between new and aged cable, as for example, Figs. 6 and 7, would seem to indicate that the brief periods of exposure in the measurements introduce no serious error.

As regards the power factor hydrophil relations, two questions arise:

1. Why should the hydrophil content in the centre of the laboratory-aged cable of Fig. 6 be so much lower than that of the new cable?

2. What is the relation of the values of power factor as measured on the individual tapes to the overall power factor of the cable?

The results indicate in very definite manner that there are two and perhaps more types of deterioration in cables. That due to ionization, the common result of which is wax formation, has long been recognized. The second type, namely, an increase of power factor due to hydrophil content is new. It is, therefore, important to examine as well as we can its probable importance. Some of the values of power factor due to this cause apparently are very high, and so constitute serious limitations or danger. On the other hand, these values pertain to the tapes alone and it is not stated what is the overall power factor of the cable. It is to be noted that a moderate increase of power factor due to oxidation, while it must be considered a deterioration, does not necessarily lead to a substantial shortening in the life of the cable. Gaseous ionization, on the other hand, is not only an active deteriorating agent, but a powerfully destructive agent. The paper offers very few data bearing on the relative importance of the two causes of deterioration, although there is distinct suggestion that they are independent of each other.

**Howard S. Phelps:** Operating experience with the thinner oils used in the higher voltage cables indicates that the electrical character or quality of these oils deteriorates progressively with time in service. The determination of the exact nature and significance of these changes is being studied intensively by various investigators.

The work reported by Messrs. Wyatt, Spring, and Fellows in their paper discloses very promising methods for attacking some of these obscure problems.

The study that the authors have made of the hydrophil content in used oils is extremely interesting since it seems to indicate that that factor should be of great assistance in investigating deterioration in service of insulating oils. Apparently it sheds considerable light on the nature of the chemical changes that take place. This results from the possibility to differentiate between types of deterioration; that is between deterioration resulting from oxidation and that resulting from polymerization which is apparently the result of ionization.

**R. L. Dodd:** Messrs. Wyatt, Spring, and Fellows have demonstrated that the increase in hydrophil content and the increase in power factor are due to the presence of air in the cable. Modern cables have substantially all of the air removed during manufacture. The small amount which remains is so uniformly distributed throughout the insulation that its effects would result only in substantially flat hydrophil and power factor curves.

We must lay the responsibility for high power factors in the tape layers nearest the surfaces to air which is admitted to the cable after it has been made. Joints and terminals which are supplied with oil from permanent reservoirs or are frequently serviced with insulating compound should be absolutely tight and permit no air to enter the cable.

It is frequently noticed that solid type cables draw in air as soon as the end seals have been removed. This is due principally to two facts, first, that the lead sheath stretches somewhat during the reeling, handling, and unreeling operations, creating a larger volume and a partial vacuum within it, and second, that the field installation temperature usually is lower than the temperature in the cable mill at the time the cable is sealed up in its lead sheath.

It is imperative that, if we are to prevent this quite common entrance of the air into the cable as soon as the seal is removed or the sheath cut, the cable ends must be at a pressure equilibrium. This equilibrium can be maintained by providing the reels with reservoirs of oil which are connected to the cable ends continuously from the time it is made until it is in its final position in the conduits. Where the cost of such equipment is not justified, the pressure equilibrium should be restored immediately before the cable sheath is opened for installation or splicing. This can be done by a device for puncturing the sheath of the cable under an oil seal and injecting cable oil under pressure until the pressure within the cable is at or above atmospheric. The latter method is one readily applied in the field to solid types of cables at a cost much less than the cost of providing the reels with reservoirs.

Such a device for reimpregnating cable ends in the field has been in use on 27,600-volt cables in Milwaukee since early in 1931. Each cable end is treated with suitable cable oil to refusal at a pressure of 15 lb per square inch above atmospheric. Some cable ends will admit no oil, while others take as much as 5 lb before refusal. The average amount admitted under this treatment varies from about ¼ lb in summer to 1 lb in winter. The average time required is less than 10 minutes.

**J. B. Whitehead:** The principal comments that have been made upon my paper fall into two classes, first, its significance as related to the solid core cable, and second, the form in which the results are reported.

Several discussors have pointed out that the life values given by us should not be used for an estimate of the life of solid core cables. I agree to this, and in fact, the paper itself states definitely that the results may be considered as applicable only under conditions in which it is certain that internal gaseous ionization is not present. We have attempted to show that with thorough impregnation and gaseous ionization absent, there are marked differences in the life of impregnated paper as related to the impregnating oil. Furthermore, we have indicated that the conditions of our test seem to approach closely to those obtaining in the oil-filled cable. I do not find in the discussion any question of the accuracy of the results and conclusions.

Messrs. Atkinson and Wyatt would prefer to present our results as short time breakdown tests rather than as accelerated life tests. In particular, the 8th power relation between stress and time is questioned. We have made no special claim for the accuracy of the latter method, but have used it as a simple and convenient method which has often been used, and in the absence of any recognized accurate method for presenting the results of accelerated life tests. Mr. Atkinson's preferred method of quoting the results in terms of voltage for a given time also will reveal the same sequence of increasing values, with increasing penetrativity, although the ratios as between different pairs of oils will be of substantially lower values than those shown by us in using the conventional relation of time for a given voltage. Mr. Atkinson's comment appears to question the value of any type of accelerated aging test for the determination of relative life. I would be interested to have his comment, for example, as to what significance if any, he would attach to our results as related to oil-filled cables.

Mr. Del Mar questions the use of a 2 mm vacuum. This value was selected as representative of wide manufacturing practice, as revealed in a series of visits to a number of factories. So far as visual gas and ionization characteristics are concerned, it gives excellent impregnation. We have made many studies with pressures down to 0.25 mm and lower, and have reported the effects of such differences in pressure on life elsewhere.

Mr. Halperin raises the question of the effective capillary radius of the paper with decreasing density of paper. We agree that with decreasing density, a point is reached where the relations we have shown do not obtain. We believe, however, that in this case the oil channels between paper fibers rather than the properties of the fibers themselves become the chief factor limiting life.

Messrs. Wyatt and Clark have commented upon the fact that our test baths are in contact with the air, and have raised the question as to the possible penetration of oxygen into our samples. We do not believe that such penetration is present in any substantial amount. The possibility of admission through ends and outer coverings is very small. There is no change in values of power factor and loss due to oxidation over the whole period of test. If such an influence is present, we cannot detect it, and it is, of course, uniform over the whole range of comparative tests.

**J. A. Scott:** Replying to Mr. Halperin on unit stresses the following table lists a comparison of *A*, results of impulse voltage tests on flat sheets (taken from Table IV) and *B*, results of impulse voltage breakdown tests made on single conductor cable

(0.187 oil-treated paper on 500,000 cir-mil stranded-copper conductor):

| | Thickness (inches) | Impulse Breakdown Voltage Kv Crest | "Average" volts/mil |
|---|---|---|---|
| *A* | 0.015 | 51.0 | 3,400 |
| *B* | 0.187 | 360.0 | 1,660 |

Obviously a direct comparison between such geometrically different configurations as A.S.T.M. disk electrodes and a lead-covered single conductor cable is to be made with caution. With this realization, however, it is of interest to note that the impulse strength is not directly proportional to thickness over this range of thickness.

**D. W. Roper:** In the paper by Messrs. Wyatt, Spring, and Fellows it is stated, "Experimentally it has been found that the molecular weight and the viscosity of the oil do vary across the radius of a used cable." Through the courtesy of Mr. Wyatt, a radial viscosity test was made on the oil removed from a piece of the 1,000-foot length of cable *A* that failed after 9 months of operation at double voltage at 108th Street, in addition to the other tests described in detail in their paper. The radial viscosity curve, Fig. 3 of this discussion, shows an increase of about tenfold in the viscosity of the oil, the maximum viscosity being at a point about one-third of the distance from the conductor to the sheath. As this is a very much larger increase than the changes in power factor or ionization factor, as stated in my paper, the radial viscosity test is a far more sensitive method of detecting changes in the impregnating compound than the ionization and power factor tests. The accelerated aging test proposed by the author will, therefore, become far more useful if the radial viscosity test and the other tests developed by Messrs. Wyatt, Spring, and Fellows are utilized in the examination of the insulation upon completion of the tests.

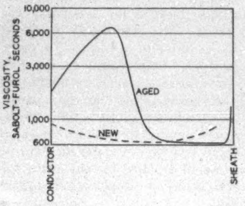

FIG. 3—VISCOSITY OF COMPOUND AT ROOM TEMPERATURE EXTRACTED FROM TAPES OF NEW AND AGED, 66-KV SINGLE CONDUCTOR CABLE OF MAKE A

Mr. Del Mar states that the dendrites originate as a rule about one-third of the way radially from the conductor surface, and this is in accord with the author's observation. It is to be noted that this point corresponds very closely with the point of maximum viscosity of the oil in the radial viscosity curve, Fig. 3 of this discussion. Mr. Del Mar also states, "If, however, the oil is thick, the gaseous ions will be obstructed and hot spots will be developed." Messrs. Wyatt, Spring, and Fellows state, "most of the oxidation products are concentrated in the oil within the paper tapes rather than in the excess interlayer oil on the outside of the tapes." Doctor Wiseman states, "Doctor Whitehead confirms the belief of some of us that the lighter oils are preferable to high viscosity oils for high electric stressed cables * * *." These statements and observations may be combined into a theory about as follows: Any change in impregnating compound is a sign of deterioration. The change occurs most rapidly when the particles of oil are restrained from shifting their position during the heat cycles. This restraint is greatest for the oil among the fibers of the paper, and it is greater for heavy oil than for light oil. The failure of the 1,000-foot cable *A* apparently was due to the very great increase in the viscosity of the oil at the point in the insulation where the signs of deterioration are first noted in similar cables. The discussion indicates that an increase in the life of the cable can be obtained, using for the impregnating compound an oil equally as good in its electrical properties, but which will not thicken under the conditions of service.

Doctor Wiseman states, "it appears that we shall go even further than heretofore in using still thinner mineral oils, particularly for the higher voltage cables * * *." Such a change appears to be quite in accord with the above theory. Several cable manufacturers in past years have mentioned informally the advantages of the thinner oils, but had expressed some fear that the compound might drain from the cable ends when they were exposed for the jointing process. During the past few years methods have been developed for connecting sections of oil-filled cable with the core filled with oil, and similar methods may be used without excessive cost in connecting lengths of the solid type of cable impregnated with much thinner oils than are now in common use. Such a change in the impregnating compound should result in insulation of greatly improved quality, thus rendering feasible further reductions in the thickness of insulation for the higher operating voltages.

The superiority of oil-filled cable containing considerable air over solid type cable made according to the same theory may be due entirely to the mobility of the oil in the oil-filled cable, as the oil used in such cables is quite fluid at all operating temperatures.

Mr. Del Mar suggests than an oil stability test, combined with the low ionization values, should serve for ordinary routine purposes. This appears to be an excellent suggestion, provided that the test is made with the oil in contact with the paper and that it is sufficiently continued so as to enable an oil to be selected which will not increase in viscosity under service conditions. Other research investigations have shown that the impregnating oil in a paper insulated cable is rendered more sensitive to change by some of the residual impurities in commerical cable papers.

Doctor Whitehead comments on the decrease of ionization factor with time of several of the cables (Fig. 11) and inquires for the cause of this wide variation amongst the values of the ionization factor shown in that figure. No information was obtained during the tests which appeared to account for the reduction of the ionization factor of several of the cables with time, but perhaps the result is due to the dispersion of redistribution of the vacuous spaces in the insulation, as Mr. Del Mar states, "Vacua are not permanent but appear, disappear, and reappear in different places, each load cycle."

Doctor Wiseman regrets that accelerated aging tests were not made on cables of later vintage than 1926. In Fig. 13 it is shown that the data were obtained from 5 cables made in 1929 and 5 in 1926. About 80 per cent of all cable subjected to the accelerated aging tests was made subsequent to 1927 and data regarding such cables, omitting the year of manufacture, are shown in Figs. 10, 11, and 12. The author regrets that the limitation of space rendered impossible a more complete exposition of the considerable improvement in cable quality subsequent to 1926.

Doctor Wiseman suggests that it seems preferable to test at moderate voltages, such as 1.5 to 1.75 times normal, for indications of instability. As stated in the paper in connection with Figs. 10 and 11, tests at 1.5 times normal voltages are unsatisfactory because they require too long a time to obtain conclusive information. Mr. Del Mar and Doctor Whitehead consider that the cost of the test even at double voltage will be very high. Obviously in order to reduce the cost of the test, it should be made at as high a voltage continuously applied as may be possible without producing results which are materially different from the changes brought about in the insulation under normal service conditions. The new tools for the examination of the insulation, developed by Messrs. Wyatt, Spring, and Fellows, will assist in determining the best voltage for the purpose. By using these new tools in the examination of the insulation of the cable samples subjected to the accelerated aging tests, and by making a similar examination of the insulation of cables which have been in service for several years, and which are removed on account of changes in the system, or failures due to external damage and other similar causes, it should be possible to prepare a curve for each type of cable showing the rate of deterioration of the cable with years of service and also to correlate this curve with a similar curve obtained from the cables subjected to the accelerated aging test. The proposed test then can be used to advantage without incorporating it in the specifications, by subjecting sample lengths of cable obtained from the various manufacturers to the accelerated aging test a few months in advance of the placing of a commercial order, and utilizing the information so obtained to select the manufacturers whose product has the lowest rate of deterioration with years of service. The information at present available indicates that the rate of deterioration for the various types of cable now in our system ranges from about 2 per cent to about 5 per cent. It further appears that in those future years in which cable is purchased the value of the 66-kv cable purchased in any one year will be at least $500,000. As practically all of the equipment required is now available, the cost of making the tests above described will not exceed 1 per cent of this figure, so that, if the test will enable cable to be selected which will have an average rate of deterioration 1 per cent per annum less than would be possible without the test, then the cost will be saved each year thereafter by the reduction in the deterioration of the cable.

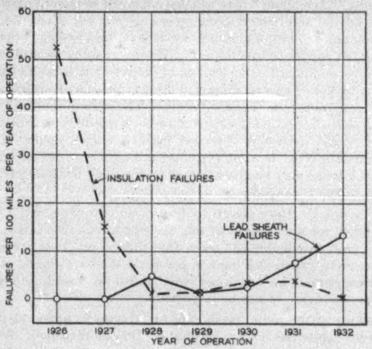

Fig. 4—Record of Replacement of 66-Kv Cable in Chicago, on Account of Failures of Insulation and Lead Sheath Failures Due to External Causes are Eliminated

The test results, reported by Doctor Wiseman, of 3,870 hours of life at 3 times normal voltage for a 66-kv cable appears to indicate that the high quality of the insulation warrants a reduction in its thickness. The statement also applies to cable *A* tested at 108th Street.

In commenting on the lead sheath troubles mentioned by the author in presenting the paper, Doctor Wiseman alleges that the cause of the failure of the lead sheath is assignable to operation, and not to quality of cable. The record of replacements of 66-kv cable due to insulation failures and to lead sheath failures is shown in Fig. 4 of this discussion. Interesting information regarding the causes of defects in lead sheaths and the means of their prevention are contained in a paper by Messrs. Dunsheath and Tunstall of W. T. Henley's Telegraph Works Company, Ltd., on "The Physical Properties of Lead Cable Sheaths" which appears in the *Journal of the I.E.E.* for March, 1928, and in a paper on "Occurrence of Irregularities in Lead Cable Sheathing and Their Relation to Cable Failures" by W. H. Bassett, Jr., and C. J. Snyder of the Anaconda Wire & Cable Co., presented to the A.I.M.E. in February, 1933.

A total of 84.4 per cent of our replacements on account of lead sheath failures was due to longitudinal splits, laminations, blisters, and dross, which, according to these two papers, are within the control of the cable manufacturer and can be eliminated by proper equipment and workmanship. In addition, 6.0 per cent of the troubles occurred where the thickness of the lead sheath was below the specified limit of tolerance in the purchase order. This makes a total of 90.4 per cent of the lead sheath troubles, which, according to other cable manufacturers, are within the control of the manufacturer. It is, therefore, very refreshing to note Mr. Del Mar's statement that "The new sheath stresses have led to intensive study of sheaths and to improvement in sheath quality."

Mr. Dambly's statement regarding the Philadelphia experience with 66-kv cables confirms the author's conclusion that the heavily loaded cables deteriorate in service faster than cables carrying lighter loads. It would even be more interesting if the data could be analyzed so as to indicate the approximate loading that causes an increase in the rate of deterioration.

**K. S. Wyatt:** We are pleased that Mr. Halperin has asked us to explain our reference to radial variations in viscosity of some cables after use because it is now clear that this may be a point of great practical importance. In making radial hydrophil and power factor measurements on a single-conductor, 66-kv cable impregnated with mineral oil compound which had been subjected to loading cycles, we noticed that as we progressed from sheath to conductor the compound varied noticeably in both color and thickness. We, therefore, measured the viscosity of the oils extracted from groups of paper tapes selected from different radial zones. The results are shown in Fig. 5. On this we have plotted also wax deposits estimated visually. The unusual radial viscosity curve led us to check our methods; this work confirmed the curve shown. Our next step was to measure radial viscosity on a sample of new cable; the resultant curve also is shown in Fig. 5. Surprisingly enough the curve is not flat; but yet it is much lower than that for the aged cable.

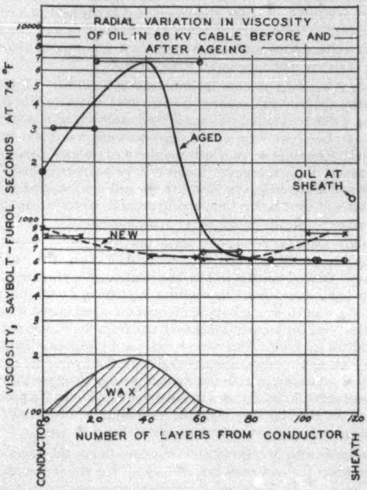

Fig. 5

It is to be noted that the peak of the wax curve roughly coincides with the peak of the viscosity curve. This observation leads us to believe the thickening of the oil was caused by gaseous ionization. It is suggested that measurement of viscosity of the oil at different radial points may be a more sensitive method of detecting whether ionization has taken place than the presence of wax.

The importance of radial changes in viscosity of cable compound lies in the possibility that they may be responsible for many failures in service. When the compound thickens, due perhaps to mild ionization, it is unable to flow outward and inward with daily heating and cooling of the cable. As a result, large voids are formed, ionization is intensified, and failure results. If this theory is true, it should be possible to devise a test whereby oils may be selected for constancy of viscosity under operating conditions. At present we are improving methods of measuring viscosity of small samples of oil and of making radial measurements on additional service-aged cables.

In answer to other questions of Mr. Halperin, repeated tests show that, at 50 volts per mil, we experience in our power factor cell no ionization. Our conclusion that ionization does not cause large increases of dielectric loss needs amplification. We meant that gaseous ionization in the cable during service, as indicated by wax deposits, does not cause large increases in the power factor of individual tapes when measured in the cell we have described; in other words, the cable's "solid loss" or loss measured at low voltage does not increase significantly as a result of ionization, of course assuming no air to be present.

It is interesting to note in commenting upon Mr. Atkinson's remarks, that several years ago we also tried measuring the power factor of different radial sections of used cable but with indifferent success. Later we were under some pressure to explain the U-shaped hydrophil curves which we obtained on used cables, and as a result, built the power factor cell we have described. The curves obtained with the power factor cell are frequently more regular and convincing than the hydrophil curves which in the first place led to the power factor measurements.

As Mr. Del Mar points out, many practical applications await the new tools. We are now proceeding with some of these applications. One of these is to test the relative ease of oxidation of paper tapes taken from new cables impregnated with different oils. We want to know how an oil oxidizes when mixed with impurities from the impregnating tank and from the paper, not how it oxidizes by itself. This we can find out by exposing the tapes to dry air and by measuring periodically the hydrophil content and power factor. In a similar manner we can compare the resistance of different insulations to discharge alone or in the presence of air. As Mr. Del Mar suggests, the radial method is useful in enabling us to discard many theories of deterioration.

We agree with Mr. Dodd's observations that solid cables draw in air when the end seals are removed. We are of the opinion that most of the U-shaped hydrophil curves we have found in service-aged cable are caused by air which has entered in this manner or at leaky joints or at the factory before leading. However, some recent evidence indicates that oxidation in certain cases may be due to other causes. We have recently re-impregnated the ends of cable samples which were put through accelerated aging tests. There is some evidence to show that this procedure is a logical precaution against entry of air and subsequent oxidation.

Doctor Race suggests another tool for layer-by-layer studies of deteriorated cable. Undoubtedly this and other tests which have been suggested, such as breakdown tests layer by layer, will give much new information in cases where deterioration has been sufficiently intense. His second suggestion that the copper and lead may catalyze oxidation at conductor and sheath and thus account for the U-shaped curves without longitudinal leakage of air is a good one. At the outset we considered this and other possibilities and with the data we then had at hand we felt that in general the odds were much against such an explanation. It may be recalled that some years ago the same question came up in connection with our studies of dissolved copper. (Association of Edison Illuminating Companies Minutes for 1930, pages 575-579, Mechanism of Cable Deterioration, Hirshfeld, Meyer and Wyatt.) Did the copper first catalyze oxidation of the oil and then react with the oxidation products or was it dispersed colloidally by gaseous ionization? With more data at hand we still feel that leakage of air along the cable is responsible for the U-shaped curves on 3-conductor cables such as we operate. Catalysis by metals would not explain the double U-shaped curves of belted typed cable such as are given in Fig. 10, where U-curves turn up at the filler space although there is no metal present. Then again where leakage is known to have occurred at potheads on accelerated aging tests only one leg of the U-curve is sometimes found, indicating, we believe, that leakage occurred along the copper conductor only. However, some recent studies on single-conductor cable lead us to believe that catalytic action of the copper or lead on dissolved air may possibly be responsible in some cases for the U-shaped curves. The most probable picture at present then is that leakage of air is the predominant cause of most of the oxidation observed in service-aged cables of the 3-conductor type. In other types of cable under special conditions where leakage may be absent other factors may become the chief cause of the U-shaped curves.

Although Dr. Race prefers hydrophil content expressed in area of spread per unit weight of oil, we believe our results are rendered more intelligible and more digestible to practical operating engineers by expressing them in per cent. We have clearly stated the assumptions on which per cent figures are based, and these assumptions should not be forgotten.

The use of the radial method as an adjunct to accelerated life tests for cables has been suggested by Doctor Wiseman. We already have some experience along this line. For a number of years we have been attempting to develop a load-cycle aging test procedure for 3-conductor cable similar to that described by Mr. Roper for single-conductor cable. We believe the load-cycle aging test to be a most valuable test for judging cable quality. In the interpretation of the results we have found the radial hydrophils and power factor to be of great assistance. For example, on some of our samples aged a few years ago, the U-curves were most pronounced. As we took greater and greater precautions in cutting the cable samples (*e.g.*, forcing in oil through the sheath before cutting to prevent inrush of air) and in pothead construction, the radial power factor curves after aging were lower in value, sometimes not greatly different from those of new cable. Not all the data fit into this picture, but there is a distinct trend. The "solid loss," *e.g.*, dielectric loss measured at low voltages, increased after aging treatment less and less as the precautions against leakage became greater. In view of this and other data we must now ask ourselves if there can be any increase in solid loss of a cable due to load-cycle aging as described by Mr. Roper if air is rigidly excluded at every step of the procedure. It now appears that possibly small increases in solid loss might take place during a 30- to 60-day test without leakage of air into the cable during preparation or aging. Any large increase in solid loss we now believe should be attributed to leakage of air. These statements apply only to modern cable of good manufacture, because of course, a great many inexplicable changes might take place in the older type cables. If this theory, of which we have partial confirmation, is correct, it would seem that there are very few, if any, accelerated tests on cables that have been run previous to the last year or two, the results of which have not been affected by oxidation. Prevention of air leakage at all stages of the aging procedure is an exceedingly difficult task because of the alternate pressure and vacua which obtain in cable from the day it leaves the factory. It also is difficult to comprehend the effect of small amounts of air on overall dielectric loss.

The inconsistencies pointed out by Doctor Whitehead may readily be explained. They do not constitute serious criticism of the method even if there were no theoretical explanation. For example, the minimum values of hydrophil content for different makes of cable vary considerably depending on the compound. This variation not only is due to different content of oxidation products but also to the area occupied on the water surface by oil globules which contain no hydrophils. The effect of a given amount of hydrophils on power factor varies with different oils for a number of reasons, one of which is that the average dissociation constant of the oxidation products varies in each case. In the case of Fig. 6 the apparent inconsistency is more readily explained. Although made by the same manufacturer, the aged cable was fabricated in 1930 and the new cable in 1933, the type of compound having been changed during the 3-year interval. However, we quite frequently find that on aging, if no oxidation has taken place, the hydrophil values drop somewhat. This may be due perhaps to polymerization of the oxidation products under operating or test conditions. It is also possible that as suggested by Doctor N. K. Adam, a portion of the oxidized molecules split up under further oxidation into smaller molecules, each containing oxygen; the small oxidized molecules are soluble in water and do not contribute to the spread. However, under normal conditions in a cable we do not believe either of these factors operates to any great extent.

We have recently obtained curves of power factor and hydrophil which very closely resemble one another. This improvement was obtained on thin oil cable by pressing out the oil from the paper by a roller-press instead of extracting it together with paper impurities by means of benzol or hexane.

Recently we have measured the power factor of the paper tapes of a 64-foot length of single-conductor high-voltage cable at 6 points along the length. The overall power factor at 60 C and 50 volts per mil calculated from the power factor of the paper tapes is 0.85 per cent. The overall power factor of the cable as measured at 60 C and 28 volts per mil is 0.75 per cent. This we consider to be a good check, since the power-factor-voltage curve for thin layers of insulation has an appreciable upward slope which is due to other influences than ionization.

We do not wish to be misunderstood as recommending the two tools described as a sure means of diagnosis of deterioration in all cases. The power factor cell is so satisfactory that it is used as a routine instrument, yet occasionally curves obtained with it are of a nondescript character. Careful sampling and quick careful measurement are necessary for check results. The hydrophil test is less satisfactory as a number of factors enter in which may upset the results. Some of these factors we do not know. In general, however, there is an unmistakable relationship between the radial hydrophil and power factor curves, particularly in the absence of other factors such as moisture. This relationship, and the shape of the radial curves in general, will prove very helpful in many cases of deterioration. Further work will uncover the cause of irregularities in the hydrophil curves; these tools will then have an even wider field of application.

# Accelerated Aging Tests on High Voltage Cable, and Their Correlation With Service Records

BY D. W. ROPER*
Fellow A.I.E.E.

***Synopsis.***—*Experience in recent years with underground cable for the higher operating voltages has developed the fact that specifications for the insulation were incomplete and inadequate, because some of its properties which were of slight importance for the lower operating voltages became of vital importance in cable for the higher voltages. Tests on impregnated paper insulation of the ordinary type as made at the factory heretofore have determined the quality of the insulation at the time of making the tests, but gave little indication of the rate or extent of the deterioration that might occur in service.*

*When the Commonwealth Edison Company, Chicago, Ill., adopted 66-kv cable for tie lines between generating stations so that the cable practically formed a high voltage bus, it became very important that the cable should be reasonably free from failures in service. Unfortunately the cable included in the first installation in 1926 fell below this requirement, and some of it had to be replaced within a few years.*

*A careful comparison of test and service records of the four makes of cable installed in 1926 showed that the cable had a wide range in quality. A marked difference was noted in the behavior of practically identical cable on a line heavily loaded and on a line moderately loaded. Accordingly, a series of tests was undertaken with the object of developing in a short time the deterioration which had been found in the several cables in service. It was found that the application of double normal voltage continuously with daily loading cycles that would heat the cable to the same copper temperature as permitted by the A.I.E.E. rules would develop in a few weeks all of the signs of deterioration that had been noted in the cable after several years of service.*

*Improvements in cable manufacture in recent years have made it possible to obtain 66-kv cable of a quality that warrants its use for important tie lines; judging by the slight deterioration that has been noted in the past few years, the cable will give a satisfactory service for many years.*

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ASSUMING that satisfactory 66-kv cable could be obtained, the Commonwealth Edison Company, Chicago, Ill., in 1926 adopted a new system plan[1] which included 66-kv underground lines of 60,000-kva carrying capacity that practically constituted a bus extending across the city and sectionalized at the generating stations. The record of failures on this cable, which began shortly after it was placed in operation late in 1926, gave unmistakable evidence (Fig. 1) that this assumption was not entirely warranted; and, further, that there were some marked differences in the quality of the insulation furnished by the different manufacturers. There resulted a great impetus to the investigations[2,3] on cable for lower operating voltages that had been in progress in Chicago for several years.

The object of the investigations forming the basis of this article was to insure that the 66-kv cable secured by the Commonwealth Edison Company for later installations would be of a quality befitting its importance on the system. This object was attained by (1) correlating the results of tests with service records, (2) devising new tests, and (3) determining proper criteria to be used with all tests so that deficient cable would be eliminated by tests at the factory before shipment.

## STATUS OF CONDITIONS

About 1918, after the large insulation losses[4] of power cables had been made apparent, it became the practice for purchasers to require a measurement of the dielectric loss[5] as a part of the factory tests. The manufacturers, in their endeavors to reduce the dielectric loss of their impregnated paper insulated, lead covered cables gradually abandoned the use of impregnating compounds consisting principally of rosin dissolved in rosin oil or in transil oil, and generally adopted mineral compounds similar to vaseline. A dielectric loss measurement was first included in American specifications about 1919. In the meantime, the change in the type of impregnating compound had resulted in the development of another kind of trouble in the insulation, called "ionization," which may become apparent only after several years of normal service and then is manifested by a rapid increase in cable failures. As a result of this situation, the cable manufacturers in 1924 reduced their guarantee period from five years to two years. This action eliminated the principal safeguard of the purchasers against cable of inferior quality and rendered necessary a revision of the test requirements included in cable specifications.

An ionization test was first included in American cable specifications in 1924. There followed shortly a considerable improvement in the thoroughness of impregnation, and about the same time the manufacturers changed from grease to heavy oils for their impregnating compounds. These changes were accompanied by a large increase in the dielectric strength (Fig. 2) as determined by the short-time high voltage test. The long-time high voltage test first introduced in 1925 also showed a marked improvement during the next few years in the initial quality of the insulation.

Farmer,[6] in a paper presented at an A.I.E.E. meeting in 1926, described the tests then being applied to impregnated paper insulated cables, their purpose, and their significance. Another paper[3] presented at the same meeting attempted to evaluate the merits of the several tests, and recognized that the specifications were inadequate in that it was possible for cable to pass all the required tests and still prove quite unsatisfactory in service.

Evidence of the difference in quality of the 66-kv

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1. For all references see list at end of paper.

*Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.*

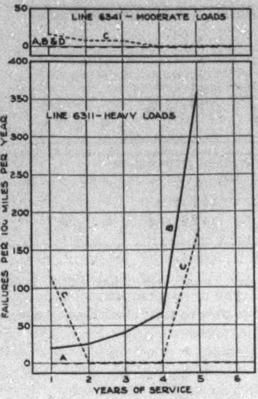

FIG. 1—RATES OF FAILURE RESULTING FROM DEFECTIVE INSULATION IN 66-KV CABLE MADE IN 1926

**Miles of Cable Installed**

| Cable | Line 6311 |
|---|---|
| A | 4.9 |
| B | 5.0 |
| C | 4.7 |
| D | 0.1 |
| Total | 14.7 |

| | Line 6341 |
|---|---|
| A | 2.7 |
| B | 4.0 |
| C | 13.0 |
| D | 10.1 |
| Total | 29.8 |

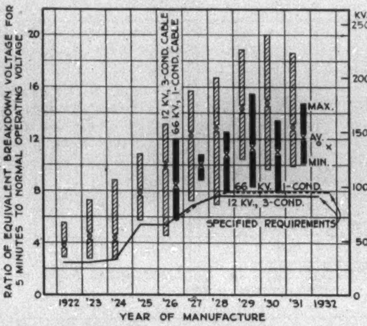

FIG. 2—RESULTS OF SHORT-TIME HIGH VOLTAGE TESTS ON 12- AND 66-KV CABLE MADE FOR COMMONWEALTH EDISON COMPANY AFTER SAMPLES HAD BEEN SUBJECTED TO THE COLD BENDING TESTS AT FACTORIES

The method of equating the test results to a voltage that will produce failure in a given time is based on Figs. 6 and 7 of Farmer's paper[4] which indicated the following relation between voltage and time to failure: $\text{Voltage} = \dfrac{\text{Constant}}{\sqrt[n]{\text{Time}}}$.
Further investigations by the Electrical Testing Laboratories (New York, N. Y.), Commonwealth Edison Company, and others confirmed this relation and indicated that $n$ should be about 6 for single-conductor cable and 7 for 3-conductor cable. With these values of $n$, the equivalent periods of time at a convenient value of voltage were calculated for each of the various steps in the actual test and were added. With this result, the equivalent voltage for the given period of time then was calculated in the same manner for the total test

cable noted shortly after the cable was placed in service, as well as information which developed later (Fig. 1) may be summarized briefly as follows:

1. Cable *A* had no insulation failures.

2. Cable *B* on the heavily loaded line (6311) had a gradual increase in the number of failures for the first three years, and then the rate of failures suddenly increased.

3. After several initially defective lengths of cable *C* on the heavily loaded line had failed and been replaced, this cable gave a perfect record for three years; then failures rapidly increased.

4. Cables *B* and *C*, which had such an unsatisfactory record on the line with heavy loads, gave much better service on another line (6341) with loads about $^2/_3$ as large.

5. Cable *D* on the lightly loaded line had no failures. Therefore, it is apparent that (a) insulation may be deficient initially and troubles will develop very quickly after the cable is placed in service; (b) the deficiency may be of a class that will not develop serious trouble for several years; and (c) the insulation may appear very deficient when the cable is required to carry full load every day, but may be satisfactory when moderately loaded for the period covered by this investigation.

## CRITICAL COMPARISON OF TEST RESULTS AND SERVICE RECORDS

*Short-Time High Voltage Test.* This test is made on a short sample (10 ft long under the lead) that has been subjected to the bending test; it consists of applying for 5 min an initial voltage nearly twice that applied to each full reel length of cable, and then increasing the voltage in steps until failure occurs.

As shown in Fig. 3, cable *A* made in 1926 was somewhat better than the other cables, and the test results for all cables were above the specification requirements. Later data in the same figure further indicate that, had the specification requirement been raised to 400 kv, for example, then cable *A*, which holds the best service record, would have been eliminated in subsequent years. From this information, it may be concluded that:

I. While the short-time high voltage test may be valuable in determining the original quality of the insulation, it is of no value as an indication of the stability of the insulation.

*Long-Time High Voltage Test.* The long-time high voltage test has been termed an accelerated life test, as it is made by the application of a voltage several times normal to a long sample (75 ft) of cable over a period of hours until the cable fails. As shown in the left side of Fig. 4, this test, made on new cable, gives results that are but little more significant of the stability of the insulation than is the short-time high voltage test.

During the first year of operation of the 66-kv cable, it was discovered by temperature surveys that as a result of local conditions about two miles of the heavily loaded line was operating at a higher temperature than the rest of the line, causing the load

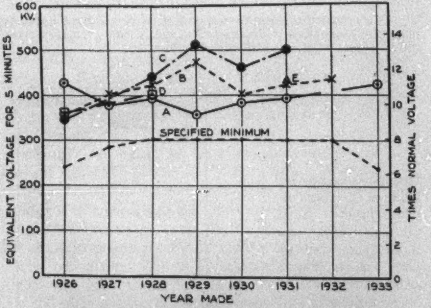

FIG. 3—AVERAGES OF RESULTS OBTAINED ON SHORT-TIME HIGH VOLTAGE TESTS ON NEW 66-KV CABLE TESTED AT FACTORIES

Equivalent voltages calculated as stated in subcaption for Fig. 2

on the entire line to be limited by the temperature of this portion. During the summer of 1928, all of the 750,000-cir mil cable in that portion of the line was replaced by 1,000,000-cir mil cable; this afforded an opportunity to make tests for determining the relative deterioration of the four original cables during their first twenty months of service. The results of the accelerated life tests on these cables shown on the right side of Fig. 4 indicate that, while cable *A* had undergone no deterioration, cables *B* and *D* had deteriorated considerably and cable *C* somewhat less.

Results of these tests were so interesting that a few lengths of cable from the lighter loaded line were removed solely for the purpose of making similar tests, with results as shown in the middle of Fig. 4. While these data indicate that cable *B* had undergone some deterioration on the two lines, the difference in the deterioration as determined by this test was insufficient to account for the difference in its service record (Fig. 1) on the two lines. Cable *B* removed from line 6341 shows more deterioration than does cable *C* removed from line 6311; consequently if this test were of value as a measure of insulation deterioration, cable *B* on line 6341 would have a poorer service record than cable *C* on line 6311. This, however, is not true, for there have been no insulation failures of cable *B* on line 6341 (Fig. 1).

From these results it appears that:

II. The long-time high voltage test applied to cables that have been in service is interesting because it gives very different results when applied to cables that when new, were of about the same quality.

III. The test is of considerable value as an indication of the quality of insulation at the beginning of the test, but is of slight value in determining the rate or extent of future deterioration.

IV. Loads to be carried are an important factor in determining the requirements for the cable.

The relative amount of visible evidence of deterioration of cables *A*, *C*, and *D* found on dissection of the samples after test was roughly proportional to the reduction in the time that they withstood the accelerated life test. Cable *B* showed proportionately much less evidence of deterioration than *C* and *D*, but it was the only one that contained rosin; hence:

V. The presence of rosin in the impregnating compound will not prevent deterioration of the insulation, but it may restrain or retard the development of visible signs of deterioration.

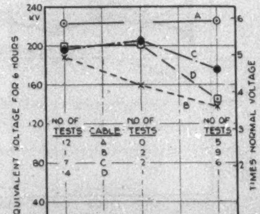

Fig. 4—Averages of Results Obtained on Long-Time High Voltage Tests on 66-Kv Cable Made in 1926; Cable Tested at Factories and in Chicago

Equivalent voltages calculated as stated in subcaption for Fig. 2

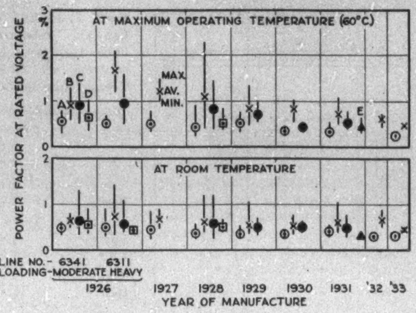

Fig. 5—Power Factors of New 66-Kv Cable Tested at Factories

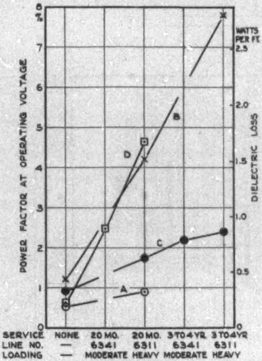

Fig. 6—Average Power Factors at 60 Deg C of 66-Kv Cable Made in 1926

*Dielectric Power Loss.* Examination of the records of initial power factor tests on insulation made at the factory on the several 66-kv cables purchased in 1926 and in subsequent years (Fig. 5) indicates no significant differences that can be correlated with the rate of deterioration of the several cables. The records in recent years show less variation in dielectric loss at the maximum operating temperature. This loss is now so low that all chance of dielectric loss failures² is eliminated, unless the loss materially increases in service.

By examining the records of sections of cable removed from time to time from the two lines under discussion (Fig. 6) interesting information is obtained on increase of power factor of cables in service. Cable *A* shows a slight increase, but even the increased loss (about 0.3 watt per foot) is very low; cables *B* and *D* show the highest increase; cable *C* shows a smaller increase and only a slight difference in deterioration on the two lines. However, cable *C* had widely differing service records on the two lines (Fig. 1). Cable *D* shows an increase in power factor as great as *B*, and neither has had any service failures on the moderately loaded line.

These results appear to warrant further conclusions:

**VI. Two distinct forms of deterioration with service may occur: (1) deterioration which is manifested only by an increase in dielectric loss; and (2) deterioration which results not only in an increase in dielectric loss, but also is accompanied by an increase in service failures.**

**VII. Initial power factor measurements give no significant prediction of the rate of deterioration in service.**

Since the increase in dielectric loss of cable *D*, as shown in Fig. 6, means that the dielectric loss increased from 2 per cent to 7 per cent of the total annual charges, it would be economical to pay 15 per cent more for this cable if the dielectric loss remained constant at the initial value throughout the life of the cable.

*Ionization Tests.* Tests are made at the factory on each length of cable to determine the ionization factor, i. e., the increase in power factor between 20 and 100 volts per mil of insulation. Test results (Fig. 7) show that cable *A* of 1926, which has had no insulation failure to date, had a much lower ionization factor than the other cables, and that cable *B* had a higher ionization factor than cable *C*. If the failures of cable *C*, due to initially defective insulation (Fig. 1) are eliminated from consideration, it is found that the relative magnitudes of the ionization factors of the 1926 cable on line 6311 give a significant indication of the relative rates of deterioration leading to failures in service.

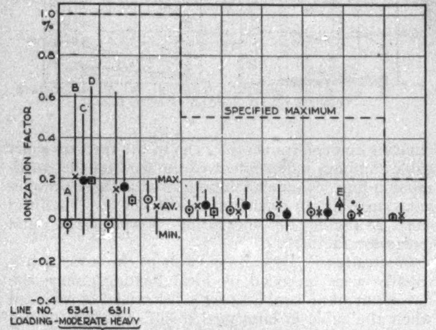

FIG. 7—IONIZATION FACTORS OF NEW 66-KV CABLE

Measurements made at factories at 40 and 200 per cent normal voltage at room temperature. Some of the negative values are probably erroneous. Only two lengths of cable *D* were on line 6311

This statement is confirmed by the record of 66-kv cable installed subsequent to 1926, since, if five failures in 1930 which occurred a few weeks after the cable was installed (thus indicating initially defective insulation) are eliminated from consideration, the three remaining insulation failures are equal to about one failure per 300 miles of cable per year of service—a highly satisfactory record. All of this cable had ionization factors of less than 0.2 of one per cent.

These data show that:

**VIII. The ionization factor for cable which is to carry full load daily should be less than 0.2 of one per cent in order to insure a satisfactory service record.**

FIG. 8—HIGH VOLTAGE LABORATORY WITH CABLE READY FOR TEST

A. Joint between cable samples
BB. Insulating sleeve
C. Terminal of circulating current transformer behind one of the high voltage transformers

If, now, the ionization factors of the cables on the two lines installed in 1926 are compared, it will be noted that:

**IX. While an ionization factor less than 0.2 of one per cent appears necessary to insure satisfactory cable on a heavily loaded line, a higher ionization factor may be satisfactory if the cable regularly carries only moderate loads.**

## ACCELERATED AGING TESTS

Since all of the tests had failed to give any significant indication of insulation stability, investigations were started for the purpose of devising a test which when applied to new cable would duplicate within a limited time the deterioration in all grades of insulation that had been noted on cables in service. Several cable manufacturers in private conference some years earlier had suggested that the suitability of impregnated paper insulation for the higher voltages be determined by subjecting the cable to excess voltage with superimposed loading cycles, and taking measurements of the power factor at intervals. Accordingly, circulating current transformers were included in the plans for the 108th Street field laboratory. After it had been determined that the loading of the 66-kv cable was an important factor in its deterioration, a series of high voltage tests with superimposed loading cycles was made on short lengths of cable. All of these tests were made on 750,000-cir mil single-conductor lead-covered cable with 750 mils of impregnated paper insulation.

*Test Conditions.* Twenty-one samples, from 25 to 50 ft long, were tested in the High Voltage Labora-

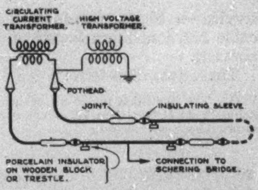
CIRCULATING CURRENT TRANSFORMER
HIGH VOLTAGE TRANSFORMER
POTHEAD
JOINT
INSULATING SLEEVE
PORCELAIN INSULATOR ON WOODEN BLOCK OR TRESTLE
CONNECTION TO SCHERING BRIDGE

Fig. 9—Circuit Diagram for Accelerated Aging Tests

Two to ten cable samples were connected in series. Pothead leads were not considered samples under test

tory by connecting several samples in series (Fig. 9) with insulating joints in their lead sheaths to exclude the joints and potheads from the measurements on the cable. The joints were made especially to prevent the movement of gas or compound into or out of the cable samples. Tests were made at various voltages from 1.5 to 3 times normal and lasted from 2 to 84 days. Heating cycles were obtained by (1) circulating current through the conductor and cooling with water through a jacket around the cable, (2) submerging the cable in oil and heating and cooling the oil, and (3) circulating current through the conductor with the cable in air, with and without current in the lead sheaths. Minimum cable temperature was room temperature while the maximum ranged from 50 to 85 deg C, i. e., from 10 deg below to 25 deg above the maximum permissible operating temperature of 60 deg C. Testing facilities were provided for measuring the power factor of any sample at any portion of the heating cycle without interrupting the current in the conductor. The longest continuous application of the voltage was 18 days.

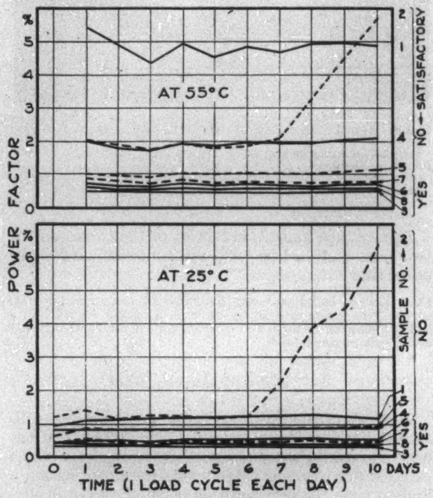

Fig. 10—Power Factors of 66-Kv Cables During First Ten Load Cycles at 57 Kv

Two samples, each 1,000 ft long, were tested also in the field laboratory (see Figs. 28 and 29 of reference 7) where they were installed in a standard conduit. These cables were connected to a bus which in turn was connected to one conductor of a 132-kv overhead transmission line, so that the cables were subjected to all the transient voltages caused by lightning and switching. The load on these cables was carried through successive cycles by using circulating current transformers as in the tests on short cable samples, independent of the load on the transmission line. Copper temperatures of these samples were varied up to a maximum of 60 deg C. Facilities were available for measuring power factor and ionization factor.

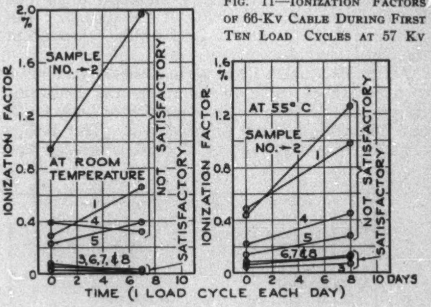

Fig. 11—Ionization Factors of 66-Kv Cable During First Ten Load Cycles at 57 Kv

*Observations.* Failures in cable of the lower grade usually were preceded by local heating; since the development of local heating is restrained or retarded when the cable is immersed in oil or water, cables tested in air gave results which best correlated with service records. With the cable in air and with double normal voltage continuously applied, about 125 per cent of maximum rated line current was required to heat the conductor to 60 deg C in 5 hr.

Tests at 1.5 times normal voltage required too long to develop definite results, and failed to exclude cables 4 and 5 (Figs. 10 and 11) which from operating records were known to be unsatisfactory. However, tests at twice normal voltage developed within a few days a marked difference in the results on two cables (Fig. 12) which had but a moderate difference in ionization factor and which had shown practically the same results in the long-time high voltage test (note IX ante). Tests at three times normal voltage failed to correlate with service records.

Significant results were obtained in the tests on short samples, from measurements of power factor at minimum and maximum temperature of each loading cycle and from measurements of ionization factor at less frequent intervals. It was noted that in the lower-grade cable large increases in dielectric loss sometimes varying over a wide range may develop during the tests, but failure may not ensue for a long period. Failures of high-grade cable with low dielectric loss may develop so rapidly that no marked increase in power factor will be noted unless the measurements are practically continuous. All failures except one occurred during the cooling portion of the loading cycle (Fig. 13). The one exception noted was the failure of one of the 1,000-ft lengths which occurred after the cable had reached minimum temperature.

Some interesting observations were made on the two 1,000-ft lengths, these cables being practically identical as determined by all other tests. Cable *A* failed after operating one month at double voltage and without load, two months with loading cycles resulting in a maximum temperature 46 deg C or less, and six additional months with loading cycles up to 60 deg C. Cable *E* failed after operating one month without load, and two months with loading cycles up to a maximum temperature of 37 deg C. Both cables showed about the same moderate amount of visible evidence of deterioration in the insulation. Cable *A* showed an increase in power factor at 20 deg C and test voltage, from 0.3 per cent to 0.5 per cent; and an increase in ionization factor at 20 deg C from 0.02 to 0.06 per cent. Cable *E* showed an increase from 0.3 per cent to 0.39 per cent in power factor, and in ionization factor at 20 deg C from 0.005 to 0.06 per cent.

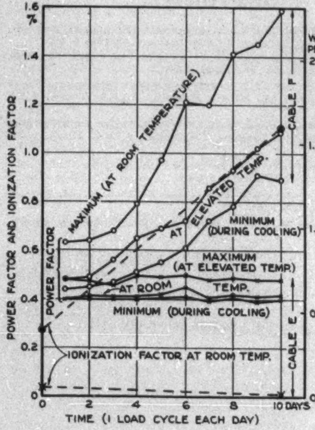

FIG. 12—(LEFT) RESULTS OF ACCELERATED AGING TEST AT DOUBLE NORMAL VOLTAGE (76 KV) WITH LOAD CYCLES RAISING CABLE TEMPERATURE TO 63 DEG C

Special samples were furnished for these tests. Results of long-time high voltage tests for cables *E* and *F* were equivalent to 276 kv and 284 kv, respectively, for 6 hr calculated as per subcaption of Fig. 2. No operating experience is available for cable *F*

Satisfactory cable upon examination showed no visible signs of deterioration at double normal voltage after tests ranging from two to nine months (Fig. 14); unsatisfactory cable *F* (Fig. 12) showed considerable evidence of deterioration after ten days. Recuperation of the insulation usually was noted with long interruptions of the voltage, and was greater for the lower-grade cable.

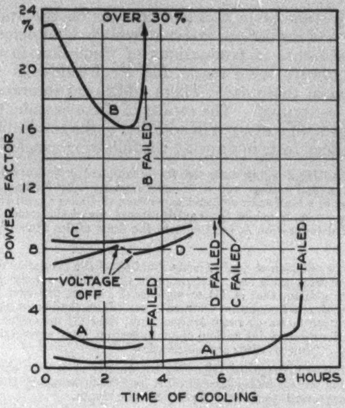

FIG. 13—POWER FACTOR OF INSULATION APPROACHING FAILURE IN LABORATORY TESTS; NOTE DROP IN POWER FACTOR FOR CABLE *D* WHEN VOLTAGE WAS REMOVED FOR 30 MIN

## CONCLUSIONS

During the years since the 66-kv cable was first installed, several sections of cable were removed from

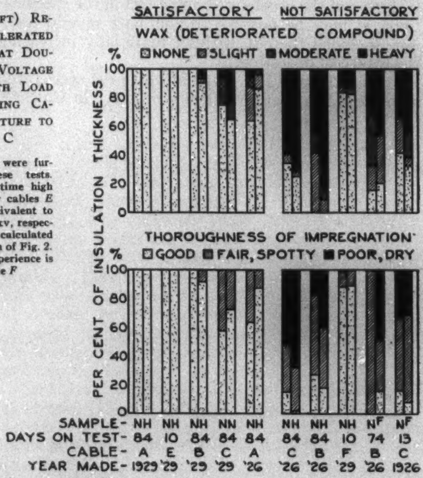

FIG. 14—DETERIORATION FOUND UPON EXAMINATION OF CABLE AFTER ACCELERATED AGING TESTS; RESULTS ARRANGED IN ORDER OF QUALITY AS DETERMINED FROM ALL INFORMATION, BEST SAMPLE ON LEFT

F, at failure H, hottest portion N, normal portion
No dendritic designs were found except at failures

time to time, as a result of changes on the system, failures of insulation, external damage, and defective lead sheaths. Examinations of insulation in such cases always were made and electrical tests were applied in those cases where additional information could be secured. The results of these examinations and tests were utilized in addition to the results of the laboratory tests in drawing the following conclusions:

X. Accelerated aging tests on 50-ft samples of 66-kv cable at double normal voltage and with superimposed daily loading cycles resulting in a maximum copper temperature of 60 deg C will develop in a few weeks, in cables of all grades tested, about the same indications of deterioration as are found in the same cables after years of service.

XI. The criterion of quality is the stability of the insulation during the accelerated aging test; there must be practically no deterioration of the insulation, that is, (1) no significant increase of power factor at maximum and minimum temperatures; (2) no significant increase in ionization factor at room temperature; and (3) no visible signs of deterioration of insulation upon dissection after completion of the test. Tests to failure are unnecessary.

XII. Better information regarding the quality of cable is obtained by testing several sections, each 50 ft long, than would be obtained by testing several times as much cable in one length.

XIII. Improvements in the manufacture of impregnated paper insulation of the ordinary type in recent years has made it possible to secure insulation for operation at 66-kv that gives very satisfactory service.

## SUGGESTIONS FOR FURTHER INVESTIGATION

Further investigations may indicate the possibility of using somewhat higher voltage than double normal in the accelerated aging test, in order to shorten the time of the test and make it less expensive. With the inclusion of the accelerated aging test in the specifications, it may be possible to eliminate several tests, now included therein, without materially increasing the total cost of testing.

During the past few years, in which the accelerated aging test has been practically in effect in Chicago, the only cable failures that have occurred apparently have resulted from local deficiencies in the insulation which cannot be detected by any known test. These defective lengths have amounted to about 0.3 of one per cent of the number of lengths installed; but, when it comes to lead sheath troubles, as Kipling would say, that is another story.

## ACKNOWLEDGMENT

The author gratefully acknowledges the fine cooperation of the Testing Department in conducting the tests in Chicago, and in particular the work of A. L. Brownlee, who developed original methods of measuring the power factor of cable with grounded sheaths and of cable with current flowing through the conductor. The author is indebted also to members of his own staff, especially to Herman Halperin, who has had general charge of the studies and assisted in the preparation of the paper, and to C. E. Betzer and H. A. Adler, who carried out the details in planning the tests and in analyzing the voluminous records.

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## Discussion

For discussion of this paper see page 1015.

# A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable

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***Synopsis.***—*Investigation of the radial variation in electrical and chemical characteristics of cable insulation between conductor and sheath is suggested as a valuable means for throwing new light on cable deterioration in service. An apparatus is described for the rapid accurate measurement of power factor of individual paper tapes taken from cable. A method is given for determining the total oxidation products in the oil from the paper tapes, layer by layer, from sheath to conductor. The results obtained by applying these methods to several types of service aged cable are reported, together with the indications which they give of the relative importance of ionization and oxidation as aging factors.*

* * * *

IT HAS long been known that paper insulated high voltage cable, when placed in service underground, suffers a gradual deterioration as evidenced by increasing dielectric loss.[1] This loss is highly undesirable because of the threat to the further life of the cable and because of the economic loss which it represents. Unfortunately the causes of such deterioration, and the manner in which it progresses, have not been quantitatively evaluated. When a faulty line has been removed from service due to inherently defective insulation, the cable engineer has lacked adequate tools with which to diagnose the basic cause of the trouble; the customary visual examination of the insulation, layer by layer, and the measurement of overall dielectric loss have been useful in a rough qualitative way only. The questions, "Does ionization as met with in service significantly increase the dielectric loss of oil impregnated paper?" and, "If oxidation is a major cause of insulation deterioration, does the oxygen come from inbreathed air, or is it released by chemical agencies from the paper?" have remained unanswered and have had to wait upon new and more delicate methods of measurement.

The conception that the origin and nature of deterioration of cable insulation might be traced by investigating the variation of the deterioration in a radial direction from sheath to conductor led to the development of 2 new procedures which should prove of great value in practical work. If, for example, the radial deterioration reached a maximum at the conductor, the inference might be drawn that it was at that point that deterioration commenced. The cause of the deterioration in such a case, it was felt, might be learned by plotting in a radial direction the pertinent physical, chemical, and electrical characteristics. In attempting to measure deterioration in this way, it was found, however, that either no methods of measuring changes in these characteristics with service aging of oil impregnated paper insulation were available, or that those in use were not sufficiently sensitive. It was only after several years' work on the measurement of the various characteristics that two methods which are sufficiently accurate to yield significant results were developed. The first of these was the determination of power factor at elevated temperature of individual paper tapes taken from cable; for this purpose a new cell was designed and constructed. The second consisted of the application of the phenomenon of spreading of oils on a water surface to determine the oxidation products in the oil from individual tapes of aged cable; this method is valuable in interpreting the radial power factor curves obtained by the first method. Both methods promise to be of great help in the solution of a number of practical problems. For this reason they will be described in detail, together with the results obtained with them in the examination of several types of cable.

## POWER FACTOR CELL FOR PAPER TAPES

In designing a practical cell for the measurement of power factor of individual paper tapes, it was necessary to meet four requirements: sensitivity, ability to maintain a constant elevated temperature during operation, accuracy, and rapidity of operation.

The completed instrument is shown in Figs. 1, 2, and 3. It is extremely simple in design. Essentially it consists of a long rectangular metal box, in the bottom of which is mounted the high voltage electrode. A long metal bar or block fitting snugly into the top opening of the box and capable of being raised and lowered, constitutes the active electrode assembly. Small openings at each end of the box permit paper tapes to be inserted between the two electrodes for measurement. Resistance heaters installed in the two slotted sidewalls provide for elevation of the temperature. All metal parts are of brass.

Sensitivity is increased by the use of extra-long electrodes (18 in.). The large amount of metal used provides a heat reserve which insures against variations in temperature due to the introduction of each new sample. Accuracy has been obtained by careful guarding of the active electrode; since the latter is only $^1/_2$ in. in width, the usual $^7/_8$-in. tape overlaps the electrode by $^3/_{16}$ in. on each side. The ease with which the sample may be introduced into the cell, properly aligned and the electrodes adjusted, and the short time required for the tape to come to

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1. For references see numbered list at end of article.

*Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.*

temperature equilibrium, make for rapidity of measurement.

The temperature of the cell as measured by a thermocouple placed in the active plate assembly is recorded automatically. It is adjustable within a reasonable range.

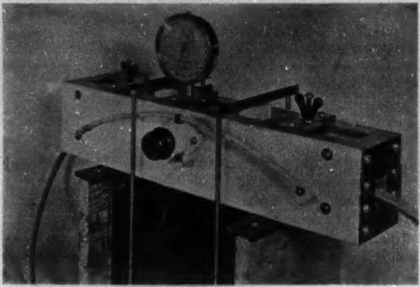


FIG. 1—CELL FOR MEASUREMENT OF POWER FACTOR OF PAPER TAPES

Good contact between the electrodes and the sample is essential for reliable measurements. In order to eliminate the effects of wrinkles in the tapes or of excess compound, pressure is applied to the movable electrode. After determining the change of power factor over a range of pressures, a value of 6.4 lb per sq in., above which no appreciable change of power factor was noted, was selected as standard for all measurements.

The thickness of the paper tapes in the cell is indicated by a dial gage. The latter provides a useful means for determining the voltage to be applied to the electrodes when a constant stress per mil is being used for measurement.

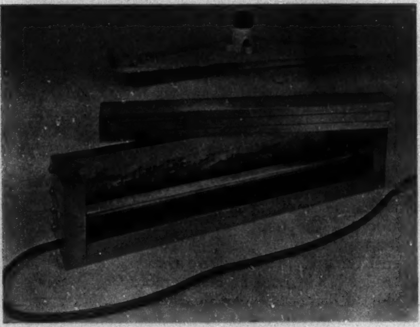


FIG. 2—INSIDE VIEW OF POWER FACTOR CELL FOR PAPER TAPES

*Measuring Equipment.* The equipment used to determine the power factor was a modified Schering bridge. The modification consisted of an auxiliary arm which makes possible the maintenance of zero potential between all active electrodes and leads, and their respective guards, thus preventing any error due to capacity current between active parts and ground. For the detector a phase shifter and an a-c galvanometer now are being used, although the early work was carried out with a less sensitive combination of synchronous commutator and d-c galvanometer.

*Procedure.* The procedure in using the cell for the measurement of power factor of cable insulation layer by layer is as follows:

A 2-ft sample is cut from the cable to be examined. The lead sheath is then removed. If the cable is of the three-conductor type, two of the conductors are stored in a glass tube filled with dry nitrogen. The shielding is removed from the remaining conductor, and the first layer of paper tape carefully unwrapped. Six inches are clipped from each end, and discarded. A short length is next cut off for the hydrophil determination to be described later. The tape is then folded in two, and inserted by means of a long thin metal guide strip into the test cell, the latter having been brought to 60 deg C, the temperature decided upon as standard for this work.

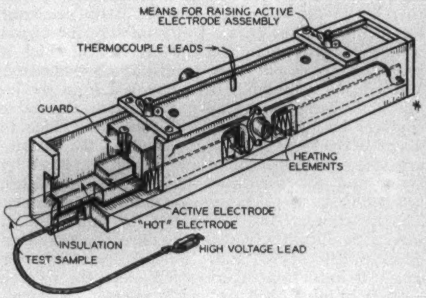


FIG. 3—CUTAWAY VIEW OF POWER FACTOR CELL FOR PAPER TAPES

A similar procedure is followed with each selected tape down to the conductor. Usually each fifth layer only is tested, except in the vicinity of the shielding and of the conductor, where sometimes it is desirable to test every layer. The practice is to delay the unwrapping of the tapes until the cell is ready for the next tape, so that exposure of the tapes to the air will be reduced to a minimum.

In operation the time required from the unwrapping of a paper tape to the completion of the power factor measurement is only 3 min. or less, an interval which has been shown to be sufficiently short to make the effects of moisture adsorption or oxidation negligible.

In early work a constant voltage of 1,000 volts

Was applied to the electrodes without making allowance for differences in thickness of the tapes. A constant stress of 50 volts per mil is now used rather than a constant voltage across the electrodes. It has been found that the power factor of oil impregnated paper tapes is somewhat dependent upon voltage, this characteristic varying with the degree of deterioration. These effects, however, are not of sufficient magnitude to sensibly alter the findings reported herein.

## THE HYDROPHIL DETERMINATION

The hydrophil test is an extremely useful method of determining the total oxidation products in an insulating oil. It was first used for this purpose by Shanklin and McKaye[2] who applied the pioneer work of Langmuir[3] on pure substances. The method has been applied successfully to the determination of the oxidation products in the oil taken from each layer from sheath to conductor of service cables. The test is invaluable in this work because of the exceedingly small sample of oil required—as little as $^{1}/_{100}$ gram may be taken as compared with 20 grams for the standard acid number test. Furthermore, the method indicates the total content of oxidation products in the oil including acids, alcohols, esters, ethers, and all other oxidation products, whereas, the acid number is an indication of the amount of one type of oxidation product only. The number of oxidized molecules determined by the hydrophil method may be over 20 times as great as that calculated from the acid number, according to Race.[4] The electrical characteristics of oil oxidized by contact with air are in general influenced more by the total number of oxidized molecules than by the number of any one type of oxidation product that may be present. For such reasons the hydrophil test should prove more valuable in determining the relation between the dielectric loss of an oil and its content of oxidized material.

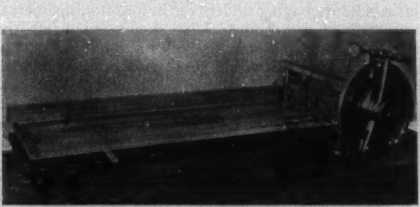


FIG. 4—FILM PRESSURE BALANCE FOR MEASUREMENT OF OXIDATION PRODUCTS IN OIL

The hydrophil content of an oil is determined by dropping on a water surface a known number of oil molecules, the number being calculated from the weight or volume of oil used. Those molecules which contain only hydrogen and carbon atoms are inert and will remain grouped as a lens without spreading. Those molecules which contain oxygen atoms are attracted by the water and spread out in a layer one molecule deep. The number of oxidized molecules is obtained by measuring the area of the spread, and dividing this value by the area occupied by each such molecule on the water surface, which is known within narrow limits.

*Apparatus.* The apparatus used for the work to be described is of the torsion type devised by N. K. Adam.[5] It consists of a long shallow paraffined brass tray on which is mounted a torsion head (Fig. 4). On the water with which the tray is filled rests a paraffined metal float which is connected to a mirror and to the torsion device. Pressure against the float is measured by reading the angle of torsion required to return a beam of light reflected by the mirror to the zero point on a vertical scale.

*Operation and Calculation.* In operation a given amount of oil, usually in benzol solution, is dropped on the water surface. The resulting film is compressed by moving a paraffined glass barrier toward the metal float, and the pressure against the float determined by the torsion device. The area of the film at this pressure is then measured. Other force-area readings are obtained by moving the glass barrier to several positions and reading the corresponding pressures. By plotting the force-area curve and extending it to cut the area axis, the area of the film at zero compression may be determined more accurately than by other methods such as those involving the use of a talc barrier. Knowing this area and the weight of oil placed on the water, the percentage of oxidation products may be calculated from the formula:

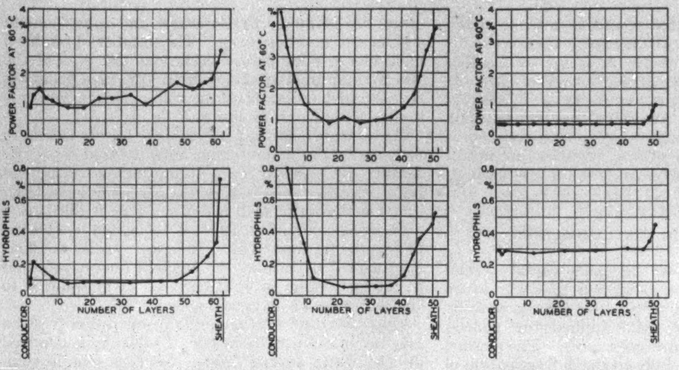
$$\text{Per cent hydrophils} = \frac{A \times M \times 100}{a \times w \times N}$$

where

$A$ = area of film at zero compression, sq cm
$a$ = area occupied by one molecule on water surface, sq cm
$M$ = average molecular weight of the oil
$w$ = weight of oil placed on water, grams
$N$ = $6.06 \times 10^{23}$ = number of molecules in a molecular weight of the oil

In applying this formula, the area occupied by each oxidized molecule is assumed to be constant, although it actually varies between 20 and 25 square Ångström units ($20 \times 10^{-14}$ to $25 \times 10^{-14}$ sq mm) for most oxidized oils, and in some cases the values may be considerably greater than 25 square Ångström units. The molecular weight of cable oils, which usually varies from 300 to 600, need not be known for comparative work, as an average value may be assumed; however, if results closer to the absolute are desired, the molecular weight of the oil should be determined.

The area of spread per gram of oil for the different layers between sheath and conductor is reported as percentage of oxidation products on the assumption that the molecular weight of the oil in each case is the same. Experimentally it has been found that the molecular weight and the viscosity of the oil do vary across the radius of a used cable. The shape of the radial hydrophil curves would not be changed, however, if it were recognized that a radial



**Figs. 5, 6, and 7—Power Factor and Oxidation Products for Individual Layers From Conductor to Sheath of Cable**

Fig. 5 (Left)—A cable after one year in service

Fig. 6 (Middle)—One core of cable, laboratory-aged by load-cycle methods

Fig. 7 (Right)—One core of new cable direct from the lead press

variation in molecular weight existed and the ordinates as plotted were labeled, "area of spread per gram of oil," instead of "per cent hydrophils."

*Procedure.* As the paper tapes are removed one by one for measurement in the power factor cell, a 3 in. to 2 ft length is clipped from each, cut into $^1/_2$ in. pieces, and dropped into a glass bottle containing 5 to 10 cu cm of benzol. After standing for about 3 hours in contact with the paper, the benzol solution is shaken up. Exactly 5 cu cm of solution are pipetted off, the benzol evaporated, and the residue weighed; in this manner the concentration of the oil in the solution is determined. At the same time a 0.1 to 1 cu cm of solution is drawn off in a standardized 1-cu cm pipette, and placed on the water surface of the film pressure balance. The area of spread, and from it the percentage of hydrophils, is then determined in the manner already described.

Certain precautions must be observed to obtain reliable results. For example, oxidation of the oil-benzol solution in contact with the paper samples takes place due to dissolved air; this can be readily detected by the sensitive hydrophil test. There is reason to believe that such oxidation is much more rapid when oils are used which have been subjected to ionization. Hence, the solutions should not be permitted to stand longer than 3 hours before measurement if accurate results are desired.

A source of error is the impurities in the chemically pure benzol as ordinarily obtained. All benzol should be redistilled, and only that fraction which boils at 79.0 to 79.1 deg C used.

It is hardly necessary to point out that care should be taken during sampling to avoid contamination by the fingers, to see that freshly distilled water is used after each run, and to recheck the calibration of the torsion device every few days.

## APPLICATION OF THE RADIAL METHOD TO AGED CABLE

With the aid of the methods described above, some 30 samples, selected from three-conductor 24-kv *H*-type cable, new and aged, have been investigated in a radial direction. All were impregnated with straight mineral oil unless otherwise stated. Typical results on service aged, acceleratedly aged, and new cables are given in Figs. 5, 6, and 7, respectively. No wax was found in any of the latter cables when they were dissected. The service aged cable was manufactured in 1927, and had been in service one year. A general similarity between the power factor and oxidation curves may be observed.

The curves of Fig. 6 were obtained from cable of 1930 manufacture. The sample tested was cut from the center section of a 45-ft length which had been on accelerated aging under continuous double operating voltage for about 2,700 hours. During the initial heating and cooling cycles a small amount of compound leaked from one pothead. The high values for oxidation products and power factor at conductor and sheath therefore might be explained on the basis of air leakage at the pothead, along the copper conductor and along the filler spaces, followed by radial penetration of the insulation.

In contrast to the results obtained with service aged cables, the radial power factor and hydrophil curves for new cable of 1931 manufacture (Fig. 7) are flat. From all these curves it is clear that deterioration of cable insulation in a radial direction is non-uniform, and that the form of the radial curves may give some clue as to the nature and cause of such deterioration.

In most cable samples all 3 conductors were examined for uniformity as to radial characteristics. The results for the 3 conductors of a 1928 mineral oil cable aged one year in service are shown in Fig. 8. In addition to radial power factor and oxidation curves, the amount of wax present in the insulation is indicated as estimated by visual examination. In this case the hydrophil curves do not explain the power factor curves as well as in the previous examples given. The explanation appears to be that in addition to oxidation another aging factor is present, namely, ionization. This is borne out to some extent by the curves for conductor 1, where the least correspondence is apparent between hydrophil value

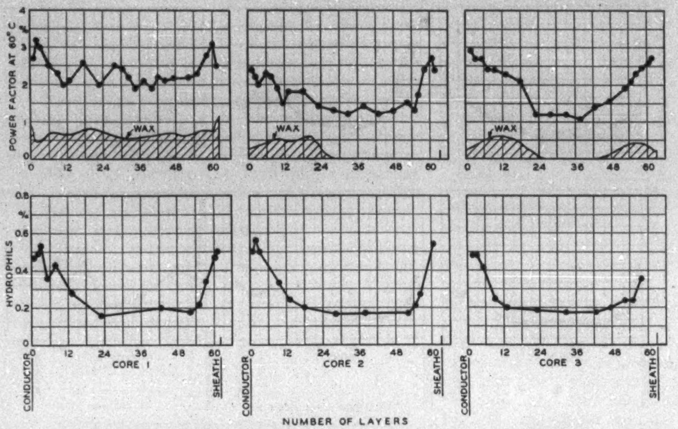


Fig. 8—Power Factor, Oxidation Products, and Wax for Individual Layers From Conductor to Sheath of Three Cores of a Cable After Four Years in Service

and power factor, but where ionization as indicated by the wax deposits has occurred with considerable intensity uniformly from conductor to sheath. The effect of ionization appears to have been to raise the middle portions of the power factor curves for conductors 2 and 3 from about 1.2 per cent to about 2.2 per cent. In any case the general level of power factor of conductor 1, where wax is in abundance throughout the insulation, is higher than in the other conductors where no wax is present in the middle portion of the insulation.

It should be noted in Fig. 8 that the character of the deterioration is different in the 3 conductors. This observation is true for a number of other cables which have been examined.

An interesting example of differences in degree of deterioration of three adjacent conductors is that of a cable which had been subjected to accelerated aging for 4,000 hours (Fig. 9). A general agreement can be observed between the character of the power factor and hydrophil curves of conductor 2 in which no wax was present; hence in this case the deviation of the radial power factor from a straight line may be satisfactorily explained as due to oxidation. In the case of conductors 1 and 3, there does not appear to be any marked similarity between the hydrophil curves and the power factor curves. Upon entering the inner 30 layers of tape which contain heavy deposits of wax the power factor curves turn downward. The wax was present in an unusual form; instead of the usual flaky appearance, it looked more like a highly viscous gum which penetrated the paper, cementing adjacent tapes together so tenaciously that they could not be separated without tearing. Moreover, whereas wax flakes as usually found are surrounded by oil, in this case the original compound appeared completely changed to the gum-like wax, so that no liquid paths for conduction were present. A plausible explanation of the lack of correspondence between the power factor and hydrophil curves where the wax is present is that the ions which are normally responsible for at least the major part of the dielectric loss are rendered almost immobile by the viscous gum and hence cannot contribute to the loss. When, however, the paper tapes are placed in benzol, solution of the gum takes place, the oxidation products are freed and may be measured as hydrophils in the usual way.

The radial method has also been applied to cables of the belted type. Instead of the single U-shaped curve between conductor and sheath often found on *H*-type cable, a double U-shaped curve (one U-shaped curve for the core and another for the belt) has been obtained on the several samples so far examined as both power factor and hydrophil curves are plotted from conductor to sheath across the core and belt insulation. Both power factor and hydrophil values for the belt are lower than for the conductor insulation. This difference may be due either to the lower temperature which is experienced by the belt tapes, since the conductor tapes pass near to the center of the cable where the temperature is highest, or to the different grade of paper which is usually used for the belt insulation.

The results on one conductor and the belt of a petrolatum cable after 8 years in service are shown in Fig. 10. In obtaining the hydrophil curves, some difficulty was experienced due to the rigidity of the oil film on the water. It was found necessary to measure the total area of spread in place of obtaining the customary force-area readings, with consequent sacrifice of accuracy. However, previous work on belted cable leaves no doubt that the radial hydrophil curves are roughly double U-shaped.

Radial measurements of hydrophils on cables containing rosin or rosin oil were at first avoided because the hydrophil determination in such cases is subject to a number of difficulties not found with straight mineral oil cables. Since rosin itself is a hydrophil, the high percentage of rosin masks the

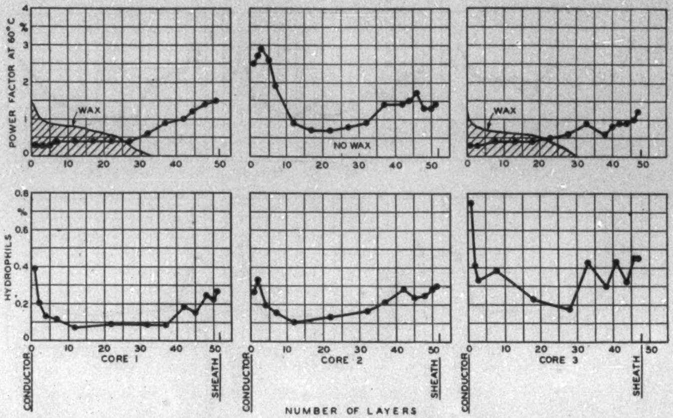


FIG. 9—POWER FACTOR, OXIDATION PRODUCTS, AND WAX FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF THREE CORES OF A CABLE, LABORATORY-AGED BY LOAD-CYCLE METHODS

small quantities of hydrophils developed by deteriorating agencies. In spite of this and other difficulties some success has attended the several attempts that have been made. Radial power factor curves on a belted-type cable containing about 6 per cent rosin are shown in Fig. 11. Here a deterioration maximum is indicated at a point intermediate between conductor and sheath. These curves are regarded as unusual, and are not typical. So far no comparison can be made between radial deterioration of cable impregnated with straight mineral oil and of that of cable impregnated with compounds containing rosin.

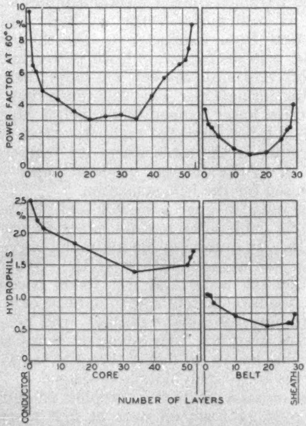


FIG. 10—POWER FACTOR AND OXIDATION PRODUCTS FOR INDIVIDUAL LAYERS FROM CONDUCTOR TO SHEATH OF ONE CORE AND THE BELT OF A BELTED-TYPE PETROLATUM-IMPREGNATED CABLE AFTER EIGHT YEARS IN SERVICE

On older type cables, manufactured previous to 1920 and in service over 10 years, the power factor curves which have been obtained are roughly U-shaped, and of very high value. It is not unusual to find the 60 deg C power factor as high as 10 per cent at the lowest point and rising to over 15 per cent at conductor and sheath.

Other types of cable in addition to the three-conductor 24-kv type have been examined radially. One abnormal type of deterioration was encountered in several samples of single conductor cable in which the 40 deg C power factor curve rose to a maximum of over 15 per cent at points intermediate between sheath and conductor, although for corresponding new cable the 60 deg C power factor curve was of low value and essentially flat, illustrated in Fig. 12. In this abnormal case of deterioration the radial hydrophil curve did not completely explain the radial power factor curve. This case is cited to show the unusual types of deterioration which may take place in service, and the value of the radial method in charting them.

## DISCUSSION

There is little doubt that the hydrophil curves in Figs. 5 to 9 represent oxidation of the insulation. The question now arises as to the source of the oxygen. There are 5 possible sources: air left in the oil or insulation at time of manufacture, air drawn in at time of installation, air breathed in at porous joint wipes or at imperfections in the lead sheath during load-cycles, moisture due to imperfect drying which might be resolved by electrolysis, or the cable paper itself. Considering the paper first it might furnish oxygen to the oil in 2 ways, either by splitting off oxygen from the cellulose molecule through the agency of ionization, or by solution in the oil of lignins, resins, and associated materials which are present in small amounts in most cable papers. Experiments appear to show that cathode ray bombardment of oil impregnated paper in vacuum does not produce oxidation of the oil as a result of disruption of the cellulose molecule, but that the oxygen-containing materials such as lignins, which are present in the cable papers, may be attacked and go into solution in the oil under bombardment. It is possible that under severe ionization they may increase the hydrophil content as much as one per cent. The effect of these materials is to promote oxidation of the oil when air is present, and probably to lower the resistivity.

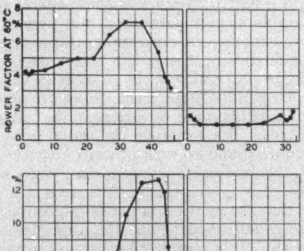


**Fig. 11—Power Factor and Oxidation Products for Individual Layers From Conductor to Sheath of One Core and the Belt of a Belted-Type Cable After Four Years in Service**

An abnormal curve obtained on a cable containing 6 per cent rosin

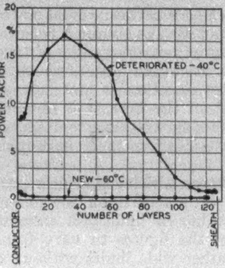


**Fig. 12—Power Factor of Individual Layers From Conductor to Sheath of a Single Conductor Cable in Which Abnormal Deterioration Has Occurred**

Air occluded in the cable during manufacture or installation, or breathed in at porous joints or leaky potheads during operation, is believed to be the principal cause of the oxidation exhibited by the radial hydrophil curves. There is some supporting evidence for this point of view. First, it is common experience that water can penetrate 50 or 100 ft along the filler spaces and between the conductor strands of *H*-type cable. Air should penetrate even farther than water; the layers of insulation near the sheath and near the conductor therefore could become oxidized, resulting in roughly U-shaped curves. It does not appear that these curves can be due to a slight a-c electrolysis of moisture in the insulation, because the shapes of the curves obtained on both *H*-type and belted cable are not consistent with such an explanation. Occasionally radial hydrophil curves were obtained in which oxidation had occurred at either the conductor or the sheath only, apparently showing that air which had penetrated along a single channel furnished the necessary oxygen. Again, it has been found that a new cable which yielded a flat radial hydrophil curve when delivered, yielded a roughly U-shaped hydrophil curve after one year's storage in spite of the fact that immediately after cutting of the original sample the cable end had been meticulously sealed; see Fig. 13. A similar finding was made on another sample which had been similarly sealed and stored for one year, Fig. 14. In this case no measurements of the types here under consideration were made upon the cable as received but there is reason to believe that the hydrophil curves were flat. The radial power factor curve of Fig. 14 tends to confirm the radial hydrophil curve and to indicate that some change has occurred in the cable. The most probable source of the deterioration appears to be oxidation due to inbreathed air.

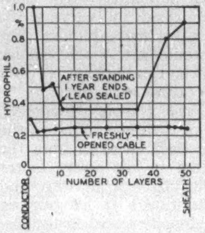


**Fig. 13—Oxidation Products of Individual Layers From Conductor to Sheath of a Cable as Received From Factory and After One Year's Storage**

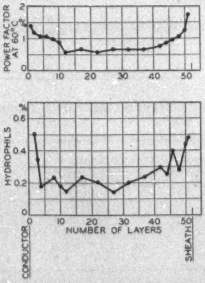


**Fig. 14—Power Factor and Oxidation Products of Individual Layers From Conductor to Sheath of New Cable After Standing Reeled for One Year**

A more exact correspondence between radial power factor and hydrophil is not always obtained because the power factor is measured on a long piece of tape whereas the hydrophils are often measured on a shorter piece. Since deterioration is not always uniform along the length of the tape, it is obvious that the power factor values may be more representative of the general deterioration than hydrophil values.

In interpreting the curves which have been presented, stress must not be placed upon the differences in the absolute value of hydrophil content which will be seen from the figures to vary from cable to cable within rather wide limits without a corresponding change in the power factor values. It cannot be expected that a constant ratio will obtain between power factor and hydrophil content, especially when different cable compounds are being compared as in the work just described. The important thing to watch for is similarity in character of the radial hydrophil and power factor curves.

In comparing the radial power factor and hydrophil curves, attention should be directed only to the correspondence of maximums and minimums, since the vertical scale of one or the other could be adjusted to produce an unfair similarity. The same end might also be accomplished by varying the temperature of the power factor measurement; the low portions of the curve would not greatly change position with temperature, whereas the high portions would be sensitive to temperature variation.

*Effects of Exposure of Tape During Measuring.* The errors due to exposure of the paper tapes to the air in the interval between their removal from the cable and their measurement in the power factor cell have been studied. The effect of moisture and oxidation together was determined by hanging up tapes in the laboratory atmosphere and measuring at intervals. The results on several tapes are given in Table I. The effect of oxidation alone was determined by placing selected tapes in a glass tube flushed out with carefully dried air. The results are given in Table II. The small change exhibited by sample 1 in Table II as compared with that of samples 2 and 3 may be explained on the basis that the latter were selected from a zone where intense ionization had taken place, resulting in the production of unsaturated hydrocarbons. The latter oxidize much more rapidly than the original oil. The effect of handling the tapes between the bare fingers cannot be detected by the power factor cell.

TABLE I—EFFECT OF EXPOSURE OF DETERIORATED PAPER TAPES TO LABORATORY ATMOSPHERE

(Average Relative Humidity = 35 Per Cent)

| Total elapsed time of exposure | | Power Factor, Per Cent | |
|---|---|---|---|
| | | Sample 1 | Sample 2 |
| Hr | Min | | |
| 0 | 0 | 2.6 | 2.8 |
| 0 | 5 | 2.6 | 2.8 |
| 0 | 50 | 3.2 | 3.5 |
| 27 | 10 | 10.2 | 10.8 |
| 48 | 40 | 10.6 | 11.8 |

TABLE II—EFFECT OF EXPOSURE OF DETERIORATED PAPER TAPES TO DRY AIR

| Total elapsed time of exposure | | Power Factor, Per Cent | | |
|---|---|---|---|---|
| | | Sample 1 | Sample 2 | Sample 3 |
| Hr | Min | | | |
| 0 | 0 | 2.4 | 1.2 | 2.7 |
| 28 | 0 | 2.4 | 4.6 | 3.8 |
| 37 | 30 | 2.5 | 4.8 | 4.1 |

From these data it may be concluded that adsorption of moisture is the major cause of increase in power factor when oil impregnated paper tapes are exposed to laboratory air, although oxidation also plays a part. Neither of these effects produces a measurable change within a 5-min period, so that the short exposure in unwrapping tapes from cable has no influence on the power factor measurement.

The hydrophil and wax characteristics which have been plotted radially for these cables are not always sufficient to explain the variations in the radial power factor curve. For example, the radial power factor is sometimes found to turn upward near the sheath, whereas the hydrophil curve is flat, even when no ionization has been present. In such a case it is thought that the increase in power factor may be due to moisture adsorbed before the application of the lead sheath. It is regrettable that so far no method for moisture determination sensitive enough for a tape-by-tape investigation is available.

Occasionally other deteriorating agencies may become sufficiently pronounced as to obscure any relationship between radial power factor curves and radial hydrophil and wax curves. Besides infiltration of moisture, solution of copper in the impregnating oil near conductor and shielding tape, which has been found to take place to a small extent in cables, may in certain cases affect the radial power factor curves.

An irregularity is frequently noted in the hydrophil curve within a few layers of conductor or sheath. This is thought to be due both to the dilution effect of the excess oil between the conductor strands, and to solution of traces of copper in the oil. The decrease in power factor of the second layer from the conductor is in some deteriorated cables marked. The effect is often found at both copper conductor and shielding tape in *H*-type cable, but only at the conductor in belted type.

An interesting observation is that most of the oxidation products are concentrated in the oil within the paper tape rather than in the excess interlayer oil on the outside of the tapes. This is shown by separate hydrophil determinations on oil wiped off the outside of the tape, and on oil dissolved by means of benzol from within the tape.

The radial method should prove of value in determining the distance from joints or leaky potheads at which oxidation effects are obtained. It should also be useful in testing the insulation in the vicinity of failures, and in determining the causes of increased dielectric loss in cable aged by accelerated methods. It also provides a means for determining the progress of deterioration with years of service. In addition many abnormal cases of service deterioration occur where the method might yield new information. On new cable, the method might be used to detect deterioration due to storage; or to bring to light errors in the manufacturing process, such as the use of oxidized oil for impregnation.

### SUMMARY

A useful method of studying the nature and source of service deterioration of oil-impregnated paper-insulated high-tension cable is to measure the electrical and chemical characteristics in a radial direction, layer by layer, from sheath to conductor. Two methods have been described for measuring, respectively, the power factor and oxidation products of individual layers of insulation. By applying these methods to used cable, a radial power factor curve is obtained which may furnish valuable information as to the *degree* and *source* of deterioration. There is also obtained a radial curve for oxidation products which, together with a radial wax curve determined by estimation, will explain in most cases the radial power factor curve, and may furnish valuable information as to the *nature* of the deterioration.

Application of the radial method to a number of used cables leads to the following conclusions:

1. Deterioration of cable insulation in a radial direction is non-uniform.
2. A major cause of deterioration of solid-type cables in service is oxidation. Oxidation also causes deterioration of cable during storage in the cable yard.
3. Leakage of air into and along the cable, either at time of installation or during operation, and air occluded in the cable at time of manufacture, are probably responsible for the oxidation of the insulation.
4. Ionization, as indicated by wax deposits, does not necessarily cause sharp increases in dielectric loss of individual paper tapes.
5. The deterioration of 3-conductor cables is frequently markedly different on 1 core than on the other 2.

The new tools should prove of practical value in the study of a number of insulation problems. They will be useful in determining the nature and source of the deterioration which goes on in cables in storage and in service, and how this deterioration progresses with years of service. They should also show the part that leaky joints and potheads play in causing deterioration and the remedial effect of oil reservoirs. They should throw new light on many abnormal types of deterioration. In addition the new tools should be helpful in checking and improving the manufacturing processes. In all cases where deterioration is experienced with thin laminated insulation as in cables, condensers, and transformers, application of the new tools should constitute a valuable diagnostic method.

### ACKNOWLEDGMENT

The work described forms part of a general research on the deterioration of high voltage cable being carried on by The Detroit Edison Company. Its conduct has entailed painstaking work on the part of many of the employees of the research department of that company. The authors wish particularly to acknowledge the work of J. M. Reynar and A. G. Fleiger who applied the hydrophil method to tape-by-tape measurements on cable; of D. E. F. Thomas, J. K. H. Sticher, and C. C. Smith who designed and applied the power factor cell; of A. A. Meyer whose suggestions have been most helpful in addition to his aid in selecting suitable samples for test; and of Professor C. S. Schoepfle of the University of Michigan, who has acted in an advisory capacity.

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## Discussion

For discussion of this paper see page 1015.

# Precision Timing of Athletic and Other Sporting Events

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PRECISE TIMING of athletic contests, aeroplane racing, and other similar sporting events in the establishing of new records against time, has been a subject of increasing interest during the last few years. A good runner will travel approximately a yard in $^1/_{10}$ of a second, and races frequently are won by a margin of inches. It is thus evident that if time records are to be employed as a common denominator for comparing athletes and for the just awarding of records, a timing system accurate to the order of $^1/_{100}$ of a second is required.

Until recently, athletic races have been timed by stop watches; experience has shown that even with competent timers, the variation of individual readings from the average indicates that the over-all probable error is undesirably large. These errors are the result of both mechanical limitations in stop watch design and errors in human judgment, which are involved in starting and stopping the watches at the proper instant. The rate of a good stop watch may be accurate to within a few seconds per day; but in the authors' observation of stop watches and measurements upon them, these rates have shown a wide variation and unless a watch is very closely adjusted and kept in good condition, it is apt to have a considerable error.

Lack of precise time measuring apparatus for athletic events long has been recognized. The requirements which formed the basis for the system to be described were outlined first by Gustavus T. Kirby, chairman of the advisory committee of the Intercollegiate Association of Amateur Athletes of America (I.C.A.A.A.A.) to whom the authors are greatly indebted for cooperation in the development and trial of the timing system.

In a track event the race is started by means of a pistol. The race begins at the visible flash of the pistol, regardless of when the sound reaches the ears of the runners or the ears of a manual timer. This may be contrary to the popular impression that the sound of the gun denotes the beginning of the race. The dependence upon sound would introduce an error of 0.27 sec in a race where the distance between starter and timers was 100 yd. The race is finished when the torso of the runner has reached a line on the ground which defines the end of the course. A tape stretched between two posts is there merely for the guidance of the runners and the judges, and has nothing to do with the finish line of the race. The standard tape consists of a loosely woven yarn and frequently it is out of line with the finish mark on the ground, because of wind pressure. The tape may be broken by a runner's hand before he crosses the line, or a runner by falling at the finish line may even finish a race without breaking the tape; because of these facts, any mechanical contrivance associated with the tape was out of the question. In addition, as far as athletic events are concerned, timing was not the sole problem; judging the position of the second, third, and sometimes the fourth runner, particularly in elimination contests, was found to be of considerable importance. Therefore, it was concluded that the only satisfactory method of timing and judging a race was by means of a motion picture camera that would photograph both the action of the contestant at the finish, and his time. Mr. Kirby, without the authors' knowledge at the time, also had arrived at the same conclusion, and a discussion and interchange of views in the summer of 1931 marked the beginning of this development. As a result of his aggressive interest and kind cooperation, the camera used has been called the Kirby Two-Eyed Camera.

### APPARATUS AND METHOD OF OPERATION

The timing system was developed primarily to meet track conditions and to enable the measurement of time with an error not to exceed one $^1/_{100}$ sec in a one-mile or shorter race. Briefly described, the system comprises a 200-cycle frequency generator, the time standard of the system; a synchronous motor; a clock driven by the synchronous motor through an electromagnetic clutch; and a high speed motion picture camera equipped with two lenses, one to photograph the action of the runner at the finish line and the other to photograph the clock. The clock consists of three concentric dials of which the inner dial, with 100 divisions, rotates at one revolution per second; the middle dial, having 60 divisions, rotates once a minute; and the outer dial, with 60 divisions, revolves at one revolution per hour. In this way it is necessary to photograph only a small segment of the three concentric dials in order to obtain the time in minutes, seconds, and hundredths seconds.

Operation of the system is evident from the schematic diagram, Fig. 1. The synchronous motor rotates continuously. The clock dials are engaged with the rotating motor by means of a polarized magnetic clutch operated by the discharge of a condenser at the beginning of the race through a contact in the starter's pistol; this starts the clock from its zero position. Just prior to the end of the

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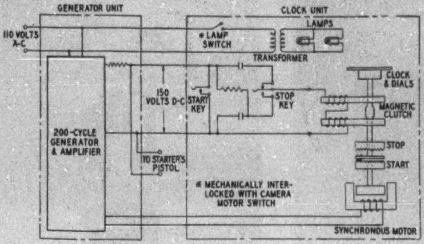

FIG. 1—SCHEMATIC DIAGRAM OF ELECTRIC TIMING SYSTEM

race the camera is operated to photograph the runner and the time registered by the clock. After the race is over, the clock mechanism is disengaged from the motor and the dials are reset to zero; the system then is ready for the next event.

## FREQUENCY GENERATOR

The 200-cycle frequency generator contains a tuning fork and an amplifying system. The tuning fork is the heart of the timing system for measurements of time are dependent upon its rate of vibration. The utmost care, therefore, has been taken in the design, construction, and operation of the tuning fork and its associated parts in order to maintain the fork frequency as closely as is practicable to 200 cycles per second. The fork itself (see Fig. 2) is made of a special alloy which reduces the effects of temperature change on frequency to a minimum. In addition, the fork is mounted in a heat insulated box provided with a thermostatically controlled heater capable of keeping the fork temperature essentially constant though the generator may be operating for an indefinite period of time in the tropics at 120 deg F or in northern winter weather of 20 deg F below zero.

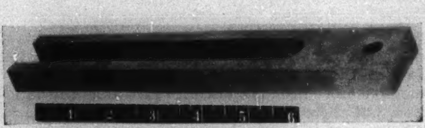

FIG. 2—THE TUNING FORK IS THE TIME STANDARD OF THE SYSTEM

Tests made under extreme temperature conditions have shown that the resulting frequency change contributes but a minor part of the total system error. The fork and the electromagnetic driving and pick-up coils are held together by a strongly built casting which, in turn, is suspended by rubber supports to eliminate the effects of external mechanical vibrations that might be of a frequency such as to change the period of vibration of the fork. As a further precaution, the whole fork box also is suspended by similar rubber supports.

Associated with the tuning fork is a three-stage vacuum tube amplifier used to maintain oscillations in the fork and also to provide the power output necessary to drive the synchronous motors. The output of the first two stages of the amplifier is coupled electromagnetically through the fork to the amplifier input so that the loss through the fork is offset by the gain in the amplifier. The fork oscillations are maintained by amplifying the small currents generated in the pick-up coils by the movement of the fork prongs, and using this amplified energy to drive the fork by means of the driving coils. A limiting device is placed in the circuit which automatically limits the amplitude of the fork with changes in line voltage of the amplifier power supply and also reasonable aging of the vacuum tubes. Such a device is necessary in order that the amplifier will not overload or the amplitude of the fork vibrations vary sufficiently to cause a change in frequency. The entire apparatus may be operated from commercial power sources with voltages from 100 to 125 volts and frequencies from 50 to 65 cycles. A photograph of the generator and clock is reproduced in Fig. 3.

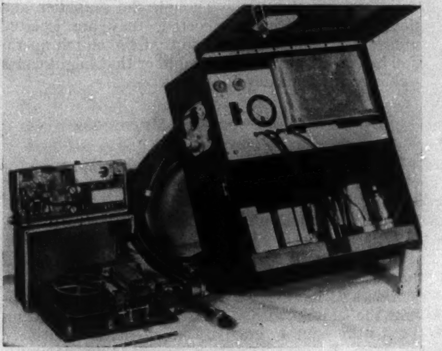

FIG. 3—AMPLIFIER USED WITH THE TUNING FORK GENERATOR, AND CAMERA CLOCK

As a further precaution to insure proper operation, a simple checking circuit is provided which permits an over-all check of the oscillating circuit and insures that the vacuum tubes are functioning satisfactorily. Although this checking circuit will not directly check the frequency of the fork, it so checks the associated circuits as to practically guarantee that the fork frequency is correct.

The third stage of the amplifier is a push-pull power amplifier which is operated by energy diverted from the tuning fork driving coils. This stage of amplification provides ample energy to drive two synchronous clocks simultaneously and is arranged so that the frequency is independent of the amplifier load. The entire equipment is operated from an a-c source, a small portion of the rectified and filtered plate power supply being used to operate

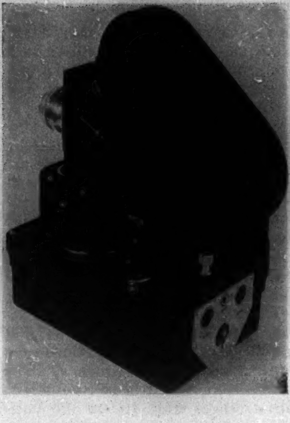

FIG. 4—CAMERA AND CLOCK ASSEMBLY

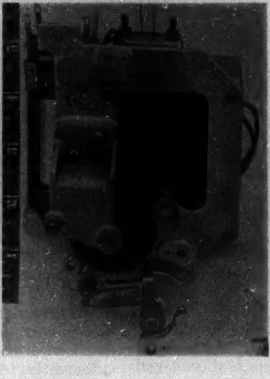

FIG. 5—SYNCHRONOUS CLOCK MOTOR; NOTE STARTING LEVER AT BOTTOM AND CLUTCH MAGNET AT LEFT

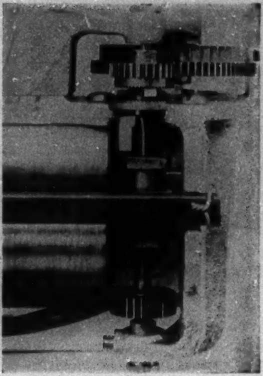

FIG. 6—POLARIZED MAGNETIC CLUTCH FOR STARTING AND STOPPING CLOCK DIALS; NOTE CLUTCH TEETH

the clutch mechanism. Though the amplifier and clutch thus are interconnected, they are isolated sufficiently well electrically so that the clutch operation has no effect upon the amplifier that might cause a change in frequency.

## THE CLOCK AND ITS MECHANISM

The clock assembly includes a synchronous motor which is connected by means of a clutch to the dials, through a gear train.

Mechanical design of the clutch and clock mechanism involved the reduction of the moment of inertia of all high speed rotating parts to a minimum, and the use of specially hardened parts for the clutch members to minimize tooth wear. In order to provide the clutch with a sufficiently high operating speed, the clutch magnets were made relatively small in size and they are operated by the discharge from a condenser. This permits the use of much greater power for a few thousandths of a second than heating limits would allow if power were applied continuously.

The dials appear on the top of the clock assembly; they can be reset by means of a peripheral ring surrounding the outside dial. A lamp house, mounted on top of the clock mechanism, provides a support for the camera and contains two ordinary 6-volt lamps for clock dial illumination. The auxiliary optical system in the camera is designed to photograph the clock dials while the main camera lens simultaneously records the action. A complete description of the camera is given in a paper by F. E. Tuttle of the Eastman Kodak Company, Rochester, N. Y., presented at the April 1933 convention of the Society of Motion Picture Engineers, held in New York, N. Y. A photograph of the camera clock assembly is reproduced in Fig. 4.

"Stop" and "start" buttons are provided on the camera clock so that it may be operated independently for testing. A jack also is provided in parallel with the "stop" key so that if the clock be used without the camera, a cord terminated in a stop switch may be inserted in this jack to permit manual stopping of the clock by a human timer; this gives instantly the time, except for the error introduced by the reaction time of the operator.

## STARTER'S PISTOL

The starter's pistol is provided with a contact inside of the butt which is adjusted to operate at the instant the hammer strikes the cartridge. Other methods have been proposed for providing this function, but the contact method seems to be the most reliable, and in hundreds of tests never has failed.

## ANALYSIS OF ERRORS IN TIMING SYSTEM

In designing a system of this type for a precision of $^1/_{100}$ sec, it has been necessary to consider carefully what errors may be involved. It will be helpful to list the possible errors and then analyze them individually. These errors are as follows:

1. Variation in standard frequency supply.
2. Error in operating the contact on the pistol.
3. Variation in phase angle of lag of synchronous clock motor.
4. Variation in operating time of clutch magnet.
5. Error due to limited number of teeth on clutch.
6. Error due to initial dial setting.
7. Observational error in reading dials.

In actual tests covering a period of several days, the frequency of a sample stock tuning fork and its associated driving circuit did not vary more than ± 9 parts in a million, when calibrated against a quartz crystal oscillator having an error less than 1 part in a million. Other sources of possible error, such as variations in the vacuum tubes used to drive the fork and in power supply voltage, make the maximum total indicated error ± 25 parts in a million, or ± 1 part in 40,000, or at a rate of about 2 sec in 24 hr. This is somewhat better than the precision generally attained in the highest grade watches. In practice, it means that in a one-mile race the error due to the fork alone will not exceed, and probably will be less than, 0.0075 sec, while in the shorter races, it will be entirely negligible, being only about 0.002 sec in the quarter-mile.

The ignition time of a cartridge has been studied exhaustively by ammunition manufacturers, and is of the order of 0.001 sec or less, depending upon the kind of powder used. Since the "start" circuit contacts do not close until the moment the cartridge is hit, the acceleration time of the trigger is not a factor.

The synchronous motor is of the variable reluctance type shown in Fig. 5. The rotor has 20 teeth and operates at 600 rpm on 200 cycles. The normal phase angle of lag is approximately 15 electrical degrees, but this angle may vary from 5 to 25 deg between minimum load with maximum input, and maximum load with minimum input. However, the error under any given conditions at a particular race will not exceed 10 electrical degrees or only 0.00014 sec.

The clutch magnet, shown in Fig. 6, has a polarized magnetic circuit and therefore tends to hold firmly in either position after operation. The starting winding is closed by the contact on the starter's pistol. The time required to operate the magnet is 0.006 sec, but the variation in this is small since both the mechanical and electrical inertia of the circuit are substantially constant. Therefore, allowance is made in the camera clock for the mean value of this error by setting the $^1/_{100}$-sec dial ahead 0.006 sec. In the case of the manually stopped auxiliary clock no such adjustment is made since the time of stopping is substantially equal to the time of starting and they thus cancel out. An allowance of 0.001 sec may be made for lack of complete compensation for this error.

Another source of error is introduced by the clutch teeth. Since there are 80 possible locking positions of the clutch, the maximum error is $^1/_{80}$ of one revolution of the motor or 0.0013 sec from this cause. High speed motion pictures of the clutch operation showed no bouncing or slippage of the clutch members, and the operation was found to be always correct to the nearest tooth.

Error due to the initial dial setting is not more than 0.001 sec if the clock dials have been adjusted properly and the operator uses ordinary care at the time of resetting. The dials are located in the correct initial position by means of a detent in the reset ring.

Error due to inaccurate reading of the dials is, of course, a human error and is largely a matter of skill in estimating fractions of the $^1/_{100}$-sec divisions on the inner dial. This should be practicable within 0.2 division or 0.002 sec.

A laboratory check on the foregoing analysis was made using two clocks which were simultaneously started and stopped 100 times by means of common push buttons, resetting between successive operations. Figure 7 shows the observed frequency distribution of the 100 differences between pairs of readings. If these differences were distributed at random in accord with the normal law of error about the observed average difference of −0.00024 sec with an rms deviation of 0.00136 sec, which is that of the observed distribution, the smooth dotted curve of Fig. 7 would be obtained. Deviations of the observed frequencies from this smooth curve are greater than may reasonably be attributed to chance variations under statistically controlled conditions. It is found, however, that the skewness of the distribution is significantly different from zero and that the observed distribution can be fitted reasonably well by the first two terms of the Gram-Charlier series; this may be taken as evidence of statistically controlled conditions where the objective distribution of error for a given system is non-symmetrical. (See "Economic Control of Quality of Manufactured Product," by W. A. Shewhart.)

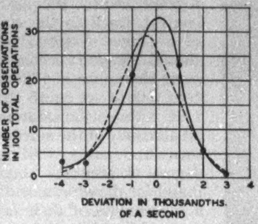

FIG. 7—FREQUENCY DISTRIBUTION OF ERROR IN OPERATION OF CLOCK

Of course, the data in Fig. 7 represent the comparison of one system against another instead of one system against an absolute standard. Assuming that for all practical purposes the objective distribution of error for one system is functionally the same as that for the other, and that the errors of one system are not correlated with those of the other, then it follows that perhaps the best estimate of the probable error of an observation for a single system is 0.00065 sec and the skewness of the single system is approximately twice that observed using the measure customarily adopted in the theory of quality control.

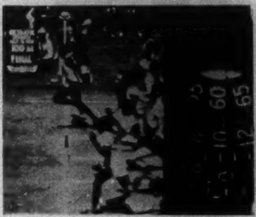

FIG. 8—FINISH OF 100-M FINAL, 1932 OLYMPIC TRYOUTS, PALO ALTO, CALIF.

The fact that the data gave this kind of evidence of statistical control supports the contention that erratic assignable causes of variability have been eliminated successfully. Furthermore, the fact that the distribution can be represented approximately by the first two terms of the Gram-Charlier series, together with the positive evidence of statistical control, leads to the conclusion that a single error of a single system due to starting and stopping should not be expected to be greater than 0.006 sec more than once in 100 times, and that it will not exceed 0.0014 sec more than 50 per cent of the time.

It is thus a fair statement to make that the overall accuracy of the system is within 0.005 sec for short races and within 0.01 sec for the mile run. This degree of accuracy should satisfy the public's demand for drawing nice distinctions in comparing the achievements of their favorite athletes, and affords a sound basis for the establishment of track records. Any higher degree of accuracy would be superfluous and inconsistent with human limitations.

## USE OF THE EQUIPMENT

On May 14, 1932, the timing system in model form had its first unofficial use at the Columbia-Syracuse track meet at Baker Field, New York, N. Y. It was used subsequently at the Princeton-Cornell meet May 21, 1932, and at the I.C.A.A.A.A. annual meet at Berkeley, Calif., in July 1932. At Palo Alto in July it was used unofficially in the Olympic tryouts. An example of the value of the device from a judging standpoint can be seen in Fig. 8, which shows five contestants bunched very close together at the finish line. Subsequent frames from the same piece of film showed definitely the order of finish of these contestants, the first three of whom were selected for the American Olympic team.

At the Xth Olympiad held in Los Angeles, July 31–August 8, 1932, the timing system was used semiofficially for every running event. It was used officially for judging but unofficially for timing inasmuch as timing to the hundredth second had not yet been recognized. Figure 9 shows the finish of the 400-m hurdle in the Olympic games; seven frames of this picture are shown in order to demonstrate the need for hundredth second timing. From the first to the seventh frame shown, the runner has advanced by only a few inches in a time of about 0.04 sec. The committee chose the middle frame as the finish of the race; the recorded time as shown is 51.67 sec. It is of interest to note after the film was viewed by the committee, that several decisions were changed at the Olympic games; the most important of these occurred in the same race illustrated in Fig. 9, in which Findlay of Great Britain was awarded third place after the medal already had been given to Keller of the United States. Figure 10 shows the effectiveness in the use of the camera clock in judging and timing the famous Tolan-Metcalfe finish in the 100-m final, where Tolan won by a very small margin.

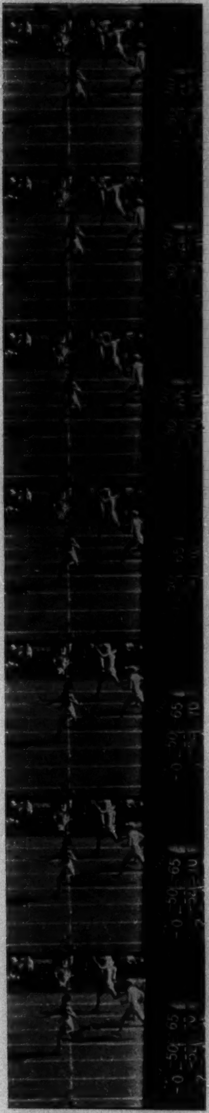
FIG. 9—FINISH OF 400-M HURDLE FINAL, XTH OLYMPIAD, LOS ANGELES, CALIF., 1932

FIG. 10—FINISH OF 100-M FINAL, XTH OLYMPIAD, LOS ANGELES, CALIF., 1932

Use of the timing system in such events as aeroplane races was demonstrated in September 1932, at the Cleveland air races. Two cameras, started together and running in synchronism, were used at the beginning and end of a straightaway speed course, in which case the elapsed time is the difference between the two readings. Figure 11 shows Major James Doolittle breaking the world's record for land planes over a 3-km course at an average speed of 294.90 mph.

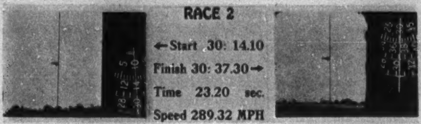

FIG. 11—MAJOR JAMES DOOLITTLE BREAKING WORLD'S SPEED RECORD FOR LAND PLANES OVER 3-KM COURSE. AVERAGE SPEED FOR FOUR CONSECUTIVE TRIALS WAS 294.90 MPH

The timing apparatus was used officially at the Amateur Athletic Union indoor meet held on February 25, 1933, in Madison Square Garden, New York, N. Y. Several races were extremely close and in the 60-yd dash the official decision was withheld until the film was viewed by the committee. At the I.C.A.A.A.A. indoor meet held on March 4, 1933, in the 258th Field Artillery Armory, New York, N. Y., the second, third, fourth, and fifth places in the 70-yd hurdle were changed from the announced decision of the judges, after they viewed the timing film. As a further result, several changes were made in team scores and Harvard replaced Princeton in fifth place.

As a result of the use of this system formal approvals have been received from the International Amateur Athletic Federation, which is the controlling body of amateur athletes for the Olympics; by the A.A.U., which is the governing body of amateur athletics in the United States; and by the I.C.A.A.A.A. Formal approval also has been given by the National Aeronautic Association; and in April 1933 approval was given by the Federation Aeronautique Internationalle, with headquarters in Paris, France, under whose regulations all official international aeroplane speed events are run.

## INDUSTRIAL APPLICATIONS

It is expected that many industrial problems will lend themselves to solution by means of the apparatus described, although time and space do not permit covering in detail that phase of precise timing. We believe that the apparatus described can be used in many places as a tool where permanent records are desired and where methods heretofore in use have not been sufficiently accurate.

# Carrier in Cable

BY A. B. CLARK* and B. W. KENDALL†
Fellow, A.I.E.E. Fellow, A.I.E.E.

***Synopsis.***—*In order to meet future demands for high grade and economical circuits in cables, considerable carrier development work has been done which has included an extensive experimental installation on a 25-mile loop of underground cable. Sufficient pairs were provided in the cable and repeaters were installed to set up nine carrier telephone circuits 850 miles long. Tests on these circuits showed the quality of transmission to be satisfactory, while the methods and devices adopted to prevent interference between them were found to be adequate. The trial therefore has demonstrated that the obtaining of large numbers of carrier telephone circuits from cable is a practicable proposition.*

*This paper is devoted largely to a description of the trial installation and an account of the experimental work which has been done in this connection. Due to present business conditions, it is expected that this method will not have immediate commercial application.*

*This work is part of a general investigation of transmission systems which are characterized by the fact that each electrical path transmits a broad band of frequencies. Such systems offer important possibilities of economy particularly for routes carrying heavy traffic. The conducting circuit is non-loaded so that the velocity of transmission is much higher than present voice-frequency loaded cable circuits. This is particularly important for very long circuits where transmission delays tend to introduce serious difficulties.*

* * * *

A TRIAL installation recently was made in which, for the first time, carrier methods were applied to wires contained wholly in overland cable for the purpose of deriving a number of telephone circuits from each pair of wires. The trial centered at Morristown, N. J. A 25-mile length of underground cable was installed in the regular ducts on the New York-Chicago route in such a manner that both ends terminated in the long lines repeater station at Morristown. The cable contained 68 No. 16 AWG (1.3 mm diam) non-loaded pairs on which the carrier was applied. Sufficient repeaters and auxiliary equipment were provided at Morristown so that these 68 pairs could be connected together with repeaters at 25-mile intervals to form the equivalent of an 850-mile 4-wire circuit.

From this 850-mile 4-wire circuit 9 carrier telephone circuits were derived, using frequencies between 4 and 40 kc. The diagram of Fig. 1 shows the system simulated by the experimental set-up.

In a practical installation the one-way paths would be shielded from each other either by placing them in separate cables or by placing them in a single cable divided into 2 electrical compartments by means of a specially arranged shield. In the set-up at Morristown the circuit was necessarily arranged somewhat differently since only one cable was available. Transmission over all loops in this cable went in the same direction, half the loops then being connected in tandem to simulate one direction of transmission through a long circuit and the other half in tandem to simulate the other direction of transmission.

It will be noted that in the cable system of Fig. 1 the practical equivalent of 2 electrical paths was provided, one for transmission in each direction, the same range of frequencies being used in each direction. This differed from common open-wire practice in which the frequency range is split in 2 and used, one half for transmission in one direction, the other half for transmission in the other. The frequency allocation of the Morristown cable carrier system is compared in Fig. 2 with existing open-wire systems in this country. Except for this matter of difference in frequency allocation, the fundamental carrier methods used in this cable system did not differ in principle from those already used on open wires. As will be noted in Fig. 2 all of these carrier telephone systems use the single sideband method of transmission with the carrier suppressed.

A schematic diagram of the terminal apparatus used in deriving one of the telephone circuits is shown in Fig. 3. Its general resemblance to the terminal apparatus used in present open-wire systems is evident so no further discussion of this seems required. Five relay rack bays carrying terminal equipment (exclusive of line amplifiers) for one system terminal yielding 9 telephone circuits are shown in Fig. 4.

Important problems in cable carrier transmission are:

1. Keeping circuits electrically separated from each other, i. e., preventing troublesome crosstalk.
2. Maintaining stability of transmission.

## CROSSTALK

With respect to crosstalk, the first and most important requirement is to secure a very high degree of electrical separation between paths transmitting in opposite directions. Careful crosstalk tests demonstrated that by placing east going circuits in one cable and west going circuits in another, the necessary degree of separation could be obtained even though the 2 cables were carried in adjacent ducts. Tests on short cable lengths indicate that adequate separation can probably be secured by means of a properly designed shield; one practical form of such a shield consists of alternate layers of copper and iron tapes. With such a shield a cable may be divided into 2 compartments and thus carry both directions of transmission.

Having thus separated opposite bound transmissions there is left the problem of keeping the crosstalk between same direction transmissions within proper bounds. In the cable used for the Morristown trial the 16 AWG pairs used for the carrier were

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separated from each other by sandwiching them in between No. 19 AWG (0.9 mm diam) quads of the usual construction. These quads served as partial shields between the carrier circuits and would in a commercial installation have been suitable for regular voice frequency use. Thus a considerable reduction in the crosstalk between the carrier pairs was effected.

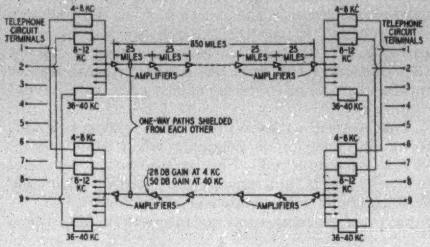

FIG. 1—SCHEMATIC OF CABLE CARRIER SYSTEM

When the problem of keeping crosstalk between circuits transmitting in the same direction within proper bounds is examined it becomes evident that no matter how high the line amplifier gains may be, these gains do not augment this crosstalk since if all of the circuits are alike transmission remains at the same level on all circuits. Not so evident perhaps is another fact that crosstalk currents due to unbalances at different points tend to arrive at the distant end of the disturbed circuit at the same time. This makes it possible to neutralize a good part of the crosstalk over a wide range of frequency by introducing compensating unbalances at only a comparatively few points. In practice, balancing at only one point in a repeater section (which may be an intermediate point or either extremity) serves to make possible considerable reduction of the crosstalk. In the Morristown set-up balancing arrangements were applied at an intermediate point in the cable and found to be entirely adequate for the frequency range involved, in fact transmission of considerably higher frequencies would have been possible without undue crosstalk. Other tests have indicated that, thanks to these balancing means, the 19-gage quads used in the Morristown cable for separating the 16-gage pairs from each other can probably be dispensed with, even for frequencies considerably above those used in the trial.

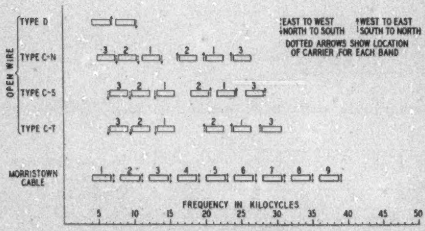

FIG. 2—FREQUENCY ALLOCATIONS OF CARRIER TELEPHONE SYSTEMS

The experimental panel on which the circuits were brought together for balancing was installed in a weather-proof hut near the center of the 25-mile repeater section. By this means all pair to pair combinations in the group to be balanced were brought into proximity so that the leads to the balancing devices could be kept short. The actual balancing was accomplished by either or both of 2 methods: (1) connecting small condensers made up of twisted pairs, between wires of different cable circuits; (2) coupling wires of different circuits together through small air-core transformers. Each unit was individually adjusted after measurement of the crosstalk between the various combinations.

## MAINTAINING STABILITY OF TRANSMISSION

Referring to the problem of stability, the importance of this will be appreciated from the fact that the average attenuation at the carrier frequencies employed in the 850-mile circuit as set up at Morristown was about 1,300 db. A circuit was actually set up and tested consisting of 9 of the carrier links in tandem, giving 7,650 miles of 2-way telephone circuit whose total attenuation without amplifiers was about 12,000 db. This attenuation, on an energy basis, amounts to $10^{1,200}$. This ratio, representing the amplification necessary, quite transcends ratios such as the size of the total universe to the size of the smallest known particle of matter.

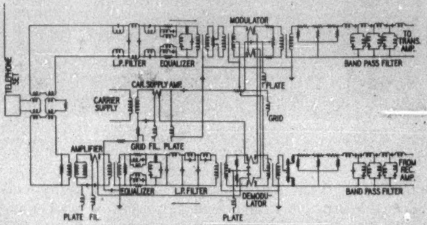

FIG. 3—TERMINAL OF ONE TELEPHONE CIRCUIT

Balancing this huge amplification against the correspondingly huge loss, to the required precision, 1 or 2 db, is a difficult problem. Fortunately, a new form of amplifier employing the principle of negative feedback has been invented by H. S. Black of Bell Telephone Laboratories and may be described later in an Institute paper. By making use of this negative feedback principle, amplifiers were produced for this job giving an amplification of 50–60 db and this amplification did not change more than 0.01 db with normal battery and tube variations. This is ample stability even when it is considered that, with amplifiers spaced 25 miles apart, there would be 160 of these in tandem on a circuit 4,000 miles long.

As is well known, the losses introduced by cable circuits do not remain constant even though the circuits are kept dry by means of the air-tight lead cable sheaths. Variation in temperature is principally responsible for the variation in efficiency of the circuits. The change in temperature, of course, alters the resistance of the wires and to a lesser extent changes the other primary constants, particularly the dielectric conductance. In Fig. 5 is shown the transmission loss plotted against frequency of a 25-mile length of 16-gage cable pair at average temperature (taken as 55 deg F) and also the effect of changing this temperature ± 18 deg F which is about the variation experienced in underground cable in this section of the country. For a circuit 1,000 miles long the yearly variation amounts to about 100 db.

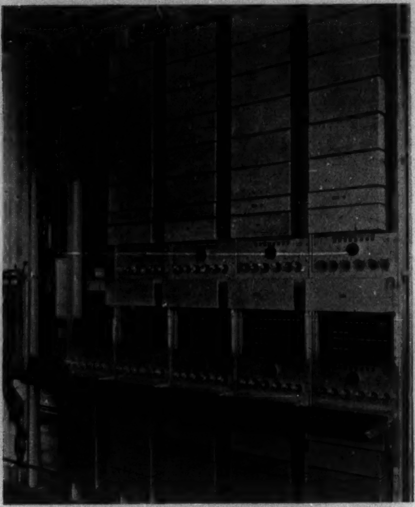

FIG. 4—TERMINAL EQUIPMENT FOR NINE TELEPHONE CIRCUITS

The transmission loss at any frequency is a simple function of the d-c resistance. Consequently, measurement of the d-c resistance of a pilot wire circuit exposed to the same temperature variations can be used to control gains and equalizer adjustments to overcome the effect of this temperature variation. In Fig. 6 is shown a schematic diagram of the pilot wire transmission regulation system used in the Morristown experiments, while the photograph of Fig. 7 indicates the appearance of the apparatus. This pilot wire regulation system takes care of a 25-mile length of cable. The arrangement of the regulating networks is such that variation of a single resistance causes the transmission loss to be varied a different amount at different frequencies as required by the variation in the line loss shown in Fig. 5. In Fig. 6 the relay system is omitted for the sake of simplicity. The function of the relay system is, of course, to control the rotation of the shaft carrying the variable resistances so that it follows the rotation of the shaft associated with the master mechanism. The centering cam is provided to avoid "hunting."

The Morristown experiments have shown that this form of regulation is adequate when underground cables are employed. Similar regulation of aerial cables in which the transmission variation with time is 3 times as large and several hundred times as rapid presents greater but not insuperable difficulties.

## OBTAINING HIGH AMPLIFICATIONS

The attenuation of cable pairs being inherently high at carrier frequencies, high amplifier gains are called for, otherwise the cost of the carrier circuits goes up very materially. Since as the power carrying capacity of the repeaters is increased a point is soon reached where it becomes very expensive to go further, high amplifications must be secured by letting the transmitted currents become very weak before amplifying them. A natural limit to this is found in the so-called thermal or resistance noise generated by all conductors. (See "Thermal Agitation of Electricity in Conductors," by J. B. Johnson, *Phys. Rev.*, v. 32, 1928, p. 97–109, and "Thermal Agitation of Electric Charge in Conductors," by H. Nyquist, *Phys. Rev.*, v. 32, 1928, p. 110–3.) Similar natural and largely insuperable noises are introduced by the vacuum tubes in the amplifiers. Other sources of noise are: (1) telegraph and signaling circuits worked on other pairs in the same cable with the carrier circuits; (2) radio stations; (3) noise from power systems, particularly electric railways. The latter 2 disturbances originate outside the cable so that they are subject to the shielding effect of the lead sheath which increases rapidly with increasing frequency. Generally speaking, in a new cable both of these and also the noises from other circuits in the same cable may be relegated by location and design to comparatively

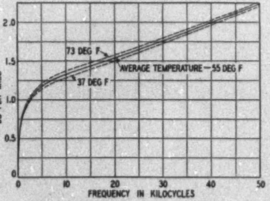

FIG. 5—TRANSMISSION LOSS OF 16-GAGE CABLE PAIR

minor importance. On existing cables, however, they may require special treatment. In all cases, however, the lower levels at the upper frequencies, which largely determine the repeater spacings, are established primarily by the thermal noise in the conductors and by the corresponding noises in the vacuum tubes. In the Morristown installation the amplifications were kept small enough and the levels high enough so that noise was not an important factor.

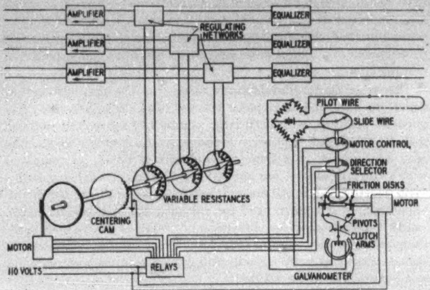

FIG. 6—AUTOMATIC TRANSMISSION REGULATING SYSTEM

## EXPERIMENTAL RESULTS

A large number and wide variety of tests have been made using the set-up at Morristown. These were generally of too technical a character to be of interest in a general paper such as this one. It will be of chief interest to note that no serious difficulty was experienced in setting up the 850-mile 4-wire 4 to 40-kc circuit with the necessary constancy of transmission loss at different frequencies, although the equalizer arrangements which made this possible presented intricate and difficult problems of design. Nine separate carrier telephone conversations were transmitted over this broad band circuit without difficulty due to cross-modulation.

Each carrier telephone circuit was designed to yield a frequency band at least 2,500 cycles wide, extending from about 250 cycles to somewhat above 2,750 cycles when 5 such carrier links are connected in tandem. This liberal frequency band and the very satisfactory linearity of transmission over the entire system, gave a very excellent quality of transmission. In order to exaggerate any quality impairment which might have been present the 9 carrier circuits were, as noted previously, connected for test in tandem giving a total length of about 7,650 miles of 2-way telephone circuit. The quality of transmission over this circuit also was found very satisfactory. In fact, the quality was not greatly impaired even when twice this length of one-way circuit was established by connecting all the lengths in tandem, giving a 15,300-mile circuit whose overall loss without amplifiers was about 24,000 db.

As noted previously, the fact that the cable pairs were left non-loaded gives the cable carrier circuits the advantage of very high transmission velocity. Including the effect of the apparatus this velocity is approximately 100,000 miles per sec; 5 or 6 times as great as the highest velocity loaded voice-frequency toll cable circuits now employed in the United States. This velocity is ample for telephoning satisfactorily over any distances possible on this earth.

## CONCLUSION

Under the present economic conditions there is no immediate demand for the installation of systems of this type. Consequently development work is being pursued further before preparing a system for commercial use. The final embodiment or embodiments of the cable carrier system will probably differ widely, therefore, from the system described in this paper. Since the transmission performance of the experimental system was so completely satisfactory, emphasis is now being directed toward producing more economical systems which will be applicable to shorter circuits. Preliminary indications from this work are that some form of cable carrier system will ultimately find important application on circuits measured in tens rather than hundreds of miles.

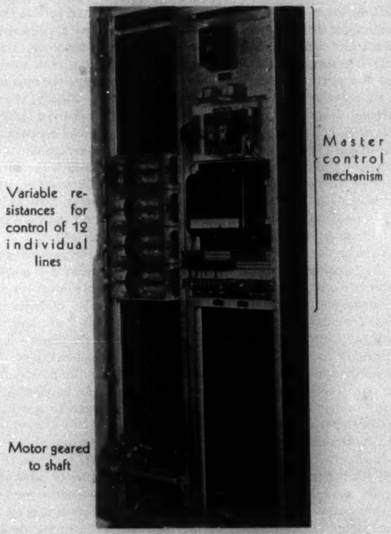

FIG. 7—AUTOMATIC TRANSMISSION REGULATING EQUIPMENT, COVERS REMOVED

## Discussion

**G. Ireland:** The initial installation of carrier telephone systems in the Bell System which were superimposed on open wire facilities was made about 1918. The history of the development and application of carrier telephone systems in the Bell System since that time has been covered in several papers presented before the Institute.[1,2] In tracing the history of the development of the carrier current systems for open wire lines, it is interesting to note the continual process of improvement and simplification which has occurred. This process including reductions in cost enlarged the field of use of carrier systems as compared to that for open wire so that, whereas the earlier systems were only justified for circuits of over several hundred miles in length present standard types of systems may prove to be economical for distances as short as 50 miles. The increased range of carrier is indicated in the following table, showing the amounts of carrier and open wire circuit miles in plant in the period from 1920 to 1930.

| | Carrier Circuit Miles | Open Wire Circuit Miles |
|---|---|---|
| 1920 | 1,000 | 1,555,000 |
| 1925 | 50,000 | 1,615,000 |
| 1930 | 500,000 | 2,100,000 |

Only about one-quarter of the open wire circuit miles is involved in circuits over about 100 miles in length, which constitutes the most common field for carrier circuits.

The earlier carrier systems were applied to existing open wire circuits that had not been initially planned for carrier superposition. This, in the case of the earlier systems, necessitated special transpositions of the open wire facilities in order to reduce the absorption effects and reduce crosstalk between systems. Later on, standardized transposition arrangements were applied to both existing and new phantom open wire lines in order to permit the operation of a number of carrier systems on the same line. Finally, the importance of obtaining a maximum use of open wire carrier facilities became so great that an entirely new form of open wire construction was adopted for new open wire facilities. The new method involved abandoning the phantoms on open wire pairs on which the carrier facilities were superimposed, reducing the spacing between the wires of these pairs to 8 inches and widening the spacing between the wires of adjacent pairs to 16 inches. This permitted the superposition of carrier telephone systems on every non-pole pair.[3]

Viewing this new development as described in the paper in light of the experience obtained with the open wire carrier, it is possible to predict that the same history of continued improvement through developments, of application first to existing cable facilities and then of increased application to both existing cable plant and new plant especially provided for such a system will take place. As in the case of the open wire carrier, it would be logical to expect that the initial applications would be made largely for the provision of the longer cable circuits and that later on it would be possible to justify economically the application of the cable carrier system to shorter and shorter distances.

**C. S. Demarest:** In the application of carrier telephony to cable circuits, the provision of office equipment that will serve to multiply the facilities obtained from a given number of cable conductors is involved. It is thus a development that tends to increase the importance of this equipment in relation to the plant as a whole. It magnifies, in this respect, the process that was started a number of years ago with the development employing small gauge toll cable conductors, with increased numbers of telephone repeaters, in place of open-wire circuits. The economies that may be effected by such developments, and their practical advantages from a plant standpoint, are, of course, greatly influenced by the design of the equipment.

Some of the equipment methods that were developed for small gauge toll cable circuits appear well suited to meeting the requirements for cable carrier. In the assembly of the equipment, for example, a method of panel mounting is employed with panels of different height but uniform length for all units. This has been designed to provide a systematic and uniform basis for assembling together within an office large numbers of units of various kinds, each unit comprising a variety of types of apparatus. Such factors have been accentuated in the equipment needed for cable carrier, in which large numbers of carrier units may sometimes be expected. The present method, therefore, has basic advantages in providing for this development in addition to facilitating its possible adaptation to the existing plant.

The cable carrier development represents the first instance in which we have had to consider the use of the relatively high frequencies involved, with such large numbers of equipment units as may be assembled together. Perhaps several hundred such units may be expected in a large cable carrier terminal, as compared with a dozen or so now encountered in a typical open wire carrier installation. This brings increased need for compactness in the carrier apparatus, with greater need for shielding between certain parts. Fairly compact arrangements were provided at Morristown with these needs in view, particularly in the case of the amplifiers, although clearances between units and groups were made very liberal as a convenience in the testing.

To reduce the amount of office cabling and provide the desired shielding between high-frequency circuits, new wiring and cabling methods have appeared desirable. The outside cable has been brought into a sealed unit located in line with the equipment in the terminal room. The conductors in this cable are soldered to individual lugs exposed only on the front of the terminal unit, and this unit is enclosed and filled with compound in the factory. This sealing of the terminal is to prevent absorption of moisture into the cable from the air more effectively than is possible with a tip cable terminated on an open frame. Between the terminal and the equipment, single lead-covered pairs with an extra shielding of copper ribbon are employed. Since these are multi-channel circuits, the number of the lead-covered pairs is relatively small.

With the long through circuits that may characterize many applications of carrier in cable, there appear to be advantages in treating the various apparatus units as fixed parts of the through system. The frequent spacing of repeaters anticipated and the fact that each of these transmits a considerable number of channels increases the importance of such an arrangement. With large groups of circuits little need is anticipated for frequent changes in the connections to the individual apparatus units comprising each circuit. In testing, with stable apparatus in prospect, there appears to be advantage in dealing with the circuit as a whole. The provision of the sealed terminal in line with the equipment, as mentioned, and the omission of the distributing frame and separate test board, are steps taken in this direction in the trial installation. Such reduction in the number of points of access to the circuits, for testing purposes, is aided by the elimination of phantoms in carrier cables.

Some of the other equipment aspects of the cable carrier development involve questions of economy and efficiency in practical application rather than necessarily novel features. The signaling means, for example, can be provided on the basis of the voice frequency signaling system now employed on ordinary cable circuits, although with the large groups of circuits expected, some other arrangements may prove more advantageous. In the case of the power supply, while the arrangements tested at Morristown have provided special features for regulation and a plate potential of over 200 volts for the amplifiers, it seems likely that standard central office voltages can be employed where this has advantages. With respect to the testing facilities for the carrier cables it appears that present means may be concentrated and simplified, and that novel types of fault locating methods may not be required. While the most effective arrangements for these various purposes are yet to be worked out, serviceable methods seem readily obtainable.

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[1] *Carrier Current Telephony and Telegraphy*, by E. H. Colpitts and O. B. Blackwell, A.I.E.E. TRANS., Vol. 40, 1921, p. 205.

[2] *Carrier Systems on Long Distance Telephone Lines*, by H. A. Affel, C. S. Demarest and I. W. Green, A.I.E.E. TRANS., Vol. 47, 1928, p. 1360.

[3] *Recent Developments in Toll Telephone Service*, by W. H. Harrison, A.I.E.E. TRANS., Vol. 49, p. 166.

As a whole, the installation of the equipment that has been provided for the Morristown trial has included the essential elements of a workable layout under commercial conditions. The tests have indicated a satisfactory degree of stability and freedom from noise in the equipment and wiring. The equipment installed for the trial has represented only the initial stage of development in its adaptation to the purpose, but generally it has appeared possible to provide arrangements that are simple and practical from a plant standpoint. Cable carrier is, of course, new, and will involve much that is new in the equipment. But it seems likely that desirable arrangements can be adapted to smooth working in the present telephone plant, and will utilize with advantage some of the basic features of present methods.

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# Beauharnois Development of the Soulanges Section of the St. Lawrence River

BY W. S. LEE*
Fellow, A.I.E.E.

**Synopsis.**—*Development of the power resources of that portion of the St. Lawrence River which forms part of the boundary between the United States and Canada, for many years has been studied by engineers and talked by politicians; and neither the end of the discussion nor the start of construction is yet in sight. Equal in magnitude of power output, but not of expenditure, is the Beauharnois development of the Soulanges section of this same river, a wholly Canadian enterprise, the initial installation of which is now in operation. The power canal of this development will form an integral part of the proposed St. Lawrence waterway. This paper describes the project as a whole in a general way and presents in more detail the principal features of the electrical installation.*

THE FIRST SECTION of the Beauharnois hydroelectric development, which has been under construction for the past 3 years, was placed in operation on October 1, 1932, by the Beauharnois (Province of Quebec, Can.) Light, Heat and Power Company, Ltd. The power station is located less than 25 miles from the city of Montreal; when completed it probably will be the largest hydroelectric station in the world as provision is made for an ultimate installation in generating capacity of 2,000,000 hp in the one station to be operated as a single unit.

The layout, design, and construction of this development is based upon step by step construction as needed to meet the power demand, thus keeping the initial expenditure at a reasonable figure, but allowing additional steps to be constructed with a minimum cost and without interfering in any way with the equipment previously installed. A unique feature of this development is that nothing was sacrificed by the adoption of step by step construction; the overall efficiency will be as high and the total capital investment will be as low as if the ultimate installation had been constructed in one operation.

Dikes for the power canal are built for full canal width; as additional water diversion is required, additional excavation will be carried on by hydraulic dredges driven electrically from power which the station itself will generate. This canal will be an integral part of the proposed St. Lawrence Waterway. The power house for the ultimate installation will be one continuous structure approximately 3,000 ft long, with one centralized point of control. The forebay will be common to the entire station, but the tailrace will be constructed in 3 sections with the spaces between tailrace sections utilized for the switching and transmission structures necessary for handling this enormous amount of power. Exceedingly careful study and cooperation was required to balance properly the hydraulic and electrical design for this feature. The three divisions of the tailrace enables one or two of them to be operated while the other is being excavated and also saves the additional cost of cofferdamming for unwatering purposes.

When complete utilization is made of the available stream flow, the development will be a complete unit, but by the adoption of the step by step construction a very efficient initial installation was secured. The initial financing required was, of course, much less than would have been required for completion of the development in one operation.

## SITE NEAR AN INDUSTRIAL AREA

Between Lake St. Francis and Lake St. Louis the St. Lawrence River has a fall of 83 ft in an air line distance of approximately 15 miles. The flow of this river is unusually uniform, the average mean flow being 220,000 cfs; maximum and minimum recorded flows in the past 70 years are, respectively, 318,000 and 173,000 cfs. Utilization of the whole mean flow represents a possible ultimate of 2,000,000 hp which can be developed at the one site at Beauharnois.

The development consists of a diversion canal between the two lakes with the power plant at the Lake St. Louis end. The diversion canal follows closely the route proposed for a navigation canal by the various international joint commissions; the Canadian government has reserved the right for such use and to construct the necessary locks between the canal and Lake St. Louis. Included in the power company's agreement with the Canadian government is a provision for the construction of control works at the head of Coteau Rapids to regulate flow and to maintain the level of Lake St. Francis. The power station is situated within 25 miles of the city of Montreal and is within convenient transmission distance of a great industrial area.

## CANAL

The canal is 15.5 miles long and extends across the relatively flat country between Lake St. Francis and Lake St. Louis. Much of the canal area is below the level of the upper lake; consequently the canal is carried between dikes for its entire length. At the Lake St. Francis end the dikes are low, increasing gradually to a maximum height of 45 ft in the vicinity of the power house forebay. The dikes are built for a channel width of 3,000 ft to take care of the ultimate diversion of 220,000 cfs. For the

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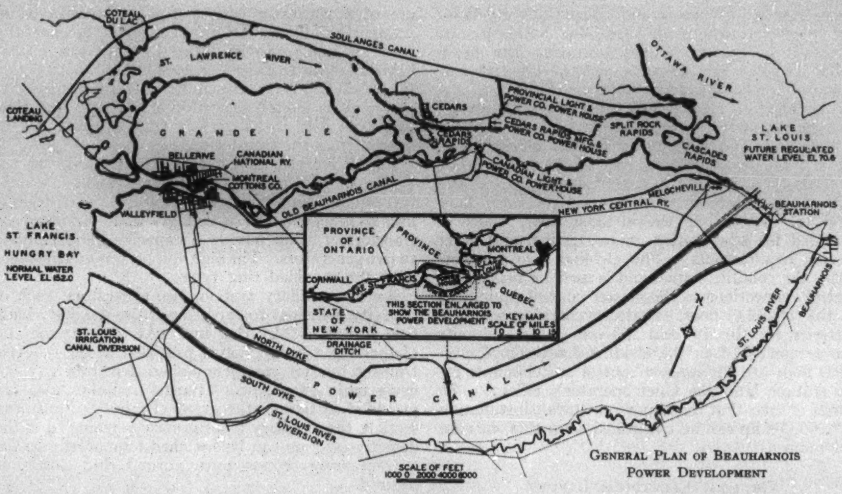

COTEAU DU LAC
SOULANGES CANAL
ST. LAWRENCE RIVER
OTTAWA RIVER
COTEAU LANDING
GRANDE ILE
CEDARS
PROVINCIAL LIGHT & POWER CO. POWER HOUSE
CEDARS RAPIDS
CEDARS RAPIDS MFG. & POWER CO. POWER HOUSE
SPLIT ROCK RAPIDS
CASCADES RAPIDS
LAKE ST. LOUIS
FUTURE REGULATED WATER LEVEL EL 70.6
BELLERIVE
CANADIAN NATIONAL RY.
MONTREAL COTTONS CO.
CANADIAN LIGHT & POWER CO. POWER HOUSE
OLD BEAUHARNOIS CANAL
MELOCHEVILLE
NEW YORK CENTRAL RY.
BEAUHARNOIS STATION
VALLEYFIELD
LAKE ST FRANCIS
HUNGRY BAY
NORMAL WATER LEVEL EL 152.0
PROVINCE OF ONTARIO
PROVINCE OF QUEBEC
MONTREAL
CORNWALL
LAKE ST. FRANCIS
LAKE ST. LOUIS
STATE OF NEW YORK
THIS SECTION ENLARGED TO SHOW THE BEAUHARNOIS POWER DEVELOPMENT
KEY MAP SCALE OF MILES 10 5 10 15
ST. LOUIS IRRIGATION CANAL DIVERSION
DRAINAGE DITCH
NORTH DYKE
SOUTH DYKE
POWER CANAL
ST. LOUIS RIVER DIVERSION
ST. LOUIS RIVER
BEAUHARNOIS
SCALE OF FEET 1000 0 2000 4000 8000

General Plan of Beauharnois Power Development

initial installation only part of the ultimate channel is excavated below ground line; as additional water diversion is required, the channel will be dredged accordingly. The canal is designed for a maximum water velocity of 2.25 ft per second.

## Power Station

While the canal excavation was chiefly in marine clay, with the exception of approximately one mile of boulder clay, the presence of a rock ledge approximately 1,000 ft wide served as an excellent foundation for the power house structure although it required that the tailrace channels be excavated from solid rock. The forebay will be common to the entire station, the north dike being so designed and located as to require minimum change for power house extension. Three independent tailraces will be provided each serving $^1/_3$ of the ultimate development. This not only allows the tailraces to be constructed one at a time as required, without interference with prior construction, but also provides adequate areas between tailraces for switching and transmission structures for the outgoing power circuits.

The present power house, approximately 1,100 ft in length, is designed for fourteen 50,000-hp generating units and two 7,800-hp station service units, and is capable of extension for the maximum of 42 50,000-hp units required for utilization of the entire mean river flow. Two 7,800-hp 60-cycle service units, two 50,000-hp 60-cycle main units, and two 50,000-hp 25-cycle main units are now in operation. To meet present power contract requirements two additional 50,000-hp 60-cycle units and four additional 50,000-hp 25-cycle units are to be installed prior to October 1937. This leaves space available for four more units to meet additional power requirements without extending the present power house. At present sluiceways are installed in the space for two units to permit by-passing water if found desirable. In order to tie in the power house structure with the north dike, it was found advantageous to extend the bulkhead structure for 4 units beyond the end of the present power house.

On the el-94.0 floor are the governors and governing equipment, water and oil supply pumps, oil filtration and storage system, space for repairing mechanical and electrical equipment, machine shop, and storage space. This floor is the main mechanical operating floor of the station, all control and indicating equipment for such operation being under the direct supervision of the turbine operators. Between the generator piers and the downstream wall is a continuous gallery of sufficient width for a 10-ton truck to traverse the length of the station, thus affording facilities for quick and convenient movement of small repair parts and other equipment. On the el-115.0 floor are the generators, motor driven exciters, generator circuit breakers, and instrument transformers used for indicating the generator output. Suspended below the el-133.0 floor are the 13.2-kv power transfer buses. On the el-133.0 floor are the individual control switchboards for each generator, metering switchboards, 550-volt auxiliary cubicles and the 13.2-kv breakers which connect into the auxiliary ring bus suspended below the el-149.5 floor. A conduit tunnel (floor el-133.0) 12 ft wide and 20 ft high extends the length of the station and connects with the conduit room below the control room and also with the conduit tunnels extending to the various switching stations. A pipe gallery (el-149.5) is provided for all piping and connections to the water and oil supply systems for the power transformers. On the bulkhead are situated the gantry cranes operating the headgates, all power transformers, and the 120-kv transformer circuit breakers. Disconnecting switches are installed on steelwork on the power house roof for isolation of station equipment.

At the east end of the power house a service building is built as an integral part of the power house structure. A lobby, superintendent's office, and general offices are situated on the generator floor level (el 115.0). On the el-133.0 floor, space is provided for laboratories, meter testing, and other service requirements. The el-146.0 floor connects with the conduit tunnel and is used for making all control connections to the master control equipment on the el-159.0 floor. Battery charging sets and batteries for the 48- and 250-volt control circuits also are installed on the el-146.0 floor. On the el-159.0 floor are the master control switchboards for the station, and the chief operator's office. The layout is such that the maximum station installation of 2,000,000 hp can be controlled from this one control room.

## General Electrical Layout

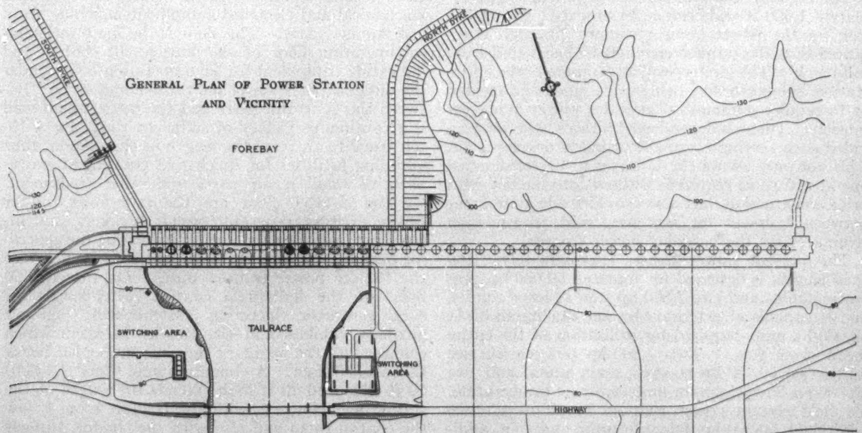
In considering the electrical layout for this station, it was realized that the units must be operated in independent groups corresponding to the requirements of the customers, but at the same time the requisite flexibility for maximum economic use of the installed equipment must be secured. One of the accompanying illustrations indicates schematically the wiring adopted for the first group of units.

For delivery of 60-cycle-power at 120-kv to the Montreal Light, Heat and Power Consolidated the use of a generator with a 3-phase step-up transformer as a unit proved most economic, no generator breakers being provided. A 13.2-kv transfer bus is installed for transfer purposes but will not be used for paralleling generating units. To supply 60-cycle power at 44 kv for construction purposes and local industrial load, a 23,250-kva transformer is fed at present from the transfer bus.

For delivery of 25-cycle power at 220-kv to the Hydro-Electric Power Commission system, a scheme was adopted involving two generators each feeding into an independent low voltage "delta" of a step-up transformer bank having a capacity corresponding to two generators. The high voltage bus arrangement is of the modified ring type.

For the auxiliary system, two generators, each of capacity sufficient to carry the entire auxiliary load, feed into a 13.2-kv ring bus. At the extreme end of the ring a connection is provided to the 60-cycle transfer bus for emergency operation from any 60-cycle main generator. Transfer switches also are provided so that in the event of failure of any ring section, the auxiliary transformer operating from the defective section can be switched temporarily to the opposite ring section until normal ring closure is secured.

Essential auxiliaries for each group of two main units are fed from a 3-phase 1,350-kva transformer, energized from an independent section of the auxiliary bus and stepping down from 13,200 to 550 volts. A transformer bank of the same rating is provided for general station auxiliaries. Circuit breakers controlling the auxiliary equipment are housed in steel cubicles on the mezzanine floor of the station (el 133.0) and are operated from the turbine operator's control and signal panels situated adjacent to the governor stands on the el-94.0 floor.


General Plan of Power Station and Vicinity

Exterior View of Present Power House ($^1/_3$ of the Ultimate) Before Construction Was Completed

### MAIN GENERATING EQUIPMENT

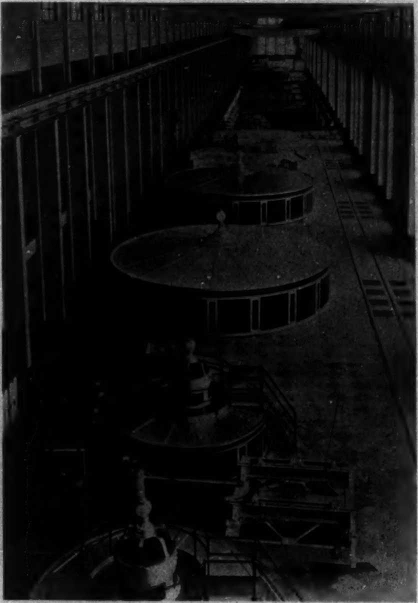
Main generating units each consist of a 75-rpm 37,300-kw generator direct connected to a 53,000-hp Francis type turbine. The 60-cycle units are rated 46,625 kva at 80-per cent power factor, 13,200 volts, 55 deg C rise; the corresponding 25-cycle units are rated 43,882 kva at 85-per cent power factor, 13,200 volts, 55 deg C rise. The 25- and 60-cycle units are identical in external appearance; they have an outside diameter of 40 ft and a height from floor line to base of signal lamp fixture of 10 ft. Both 25- and 60-cycle units are capable of continuous operation at 14,520 volts at full rated kva. To insure stability, a rotor $WR^2$ of 110,000,000 (moment of inertia about its own axis in lb-ft$^2$) was specified for both 25- and 60-cycle units, together with a short circuit ratio of 1.00 for the 60-cycle units and 1.25 for the 25-cycle units. The higher short circuit ratio for the 25-cycle units was required because the units feed into the extensive 220-kv network of the Hydro-Electric Power Commission. The generators are provided with two independent windings per phase, current transformers for the relaying system being installed in each end of each winding. To simplify terminal connections, these current transformers are mounted inside of the generator frame where ample space is available.

The weight of the rotating element plus the hydraulic thrust is carried by a thrust bearing below the rotor. This arrangement reduced the generator weight and height, and facilitates dismantling the unit as the rotor can be lifted from the generator shaft without dismantling the thrust bearing. Guide bearings are provided above and below the rotor, and an adjustable lignum-vitae guide bearing is provided for the runner. A complete unit oiling system is provided for each generating unit.

Governor stands are situated on the operating floor (el 94.0) in close proximity to the servo-motors and all governing equipment, all of which is arranged in right and left pairs between each group of two units. The mechanical and electrical equipment is so installed that two generating units constitute a complete 100,000-hp unit that can be operated as a separate and independent station.

### STATION SERVICE GENERATING EQUIPMENT

The two station service units each consist of an 180-rpm, 60-cycle generator rated 5,760 kw, 7,200 kva at 80-per cent power factor, 13,200 volts, 55 deg C rise, direct connected to a 7,800-hp Francis type turbine. The general layout is similar to that of the main units except that the conventional design of generator is used with the thrust bearing above the rotor. The generators are provided with direct connected exciters. Generator windings consist of



Interior View of the Power House Before Construction Was Completed

Steel Work of the 220-Kv Switching Station May Be Seen Near the Far End of the Bridge Over the Tailrace

a single circuit per phase with a current transformer installed in each end of each winding; these transformers are mounted inside of the generator frame.

### Excitation System

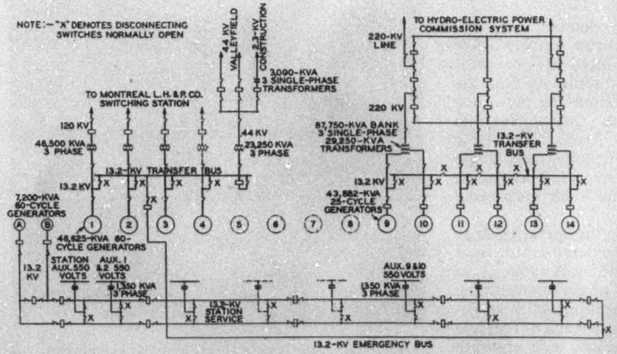
Each main generator is provided with an individual three-unit motor-driven exciter set consisting of a 320-kw 250-volt shunt-wound separately excited d-c generator, a 4-kw 250/250-volt compound-wound sub-exciter, and a 1,200-rpm 550-volt line start squirrel-cage induction motor. To reduce the length of field leads to a minimum, as well as to allow crane handling, the exciter sets are located on the generator floor adjacent to the corresponding generators. To facilitate replacing a defective exciter set with a spare, the bottoms of the set bases are planed and are supported on planed H-beams set in concrete. With this arrangement a spare exciter unit can be set in place without the time delay incident to alignment. Exciter sets for the 25- and 60-cycle generators are identical. An individual voltage regulator operated by a torque motor in conjunction with a bridge type rheostat in the exciter field provides high speed excitation for each main generator. The excitation system is designed for a rate of response of 200 volts per second and for a stable exciter voltage range from residual voltage to the ceiling voltage of 300 volts.

The direct connected exciter on each of the station service generating units is controlled by a voltage regulator of the same type as those installed for the main units, except for the omission of the high speed contactors; this regulator is used in conjunction with a motor operated rheostat in the exciter field. As the two service units operate in parallel, cross compensation is provided.

### Power Transformers

All power transformers are located on the bulkhead in the space corresponding to their generating equipment, thus reducing the low voltage bus length to a minimum. Transfer cars and tracks are provided on the bulkhead; by using the gantry crane, the transformers can be lowered to a similar transfer equipment at ground elevation (115.0) and thence brought into the power house where a repair pit is provided. A complete oil pump, filter press, and storage and piping system is provided so that the transformer oil can be drained, filtered, or replaced conveniently. Water supply pumps are in duplicate, 550-volt power for the driving motors being taken from separate auxiliary transformer banks.

For delivery of 25-cycle power at 220 kv, three-single phase water-cooled transformers are used, each rated 29,250 kva, 50 deg C rise; they are Δ-connected on the low voltage side and star-connected on the high voltage side to transform from 13.2 to 218 kv, these rated voltages being based upon full rated kva at 85 per cent power factor. Each transformer has two low volt-


NOTE:—"X" DENOTES DISCONNECTING SWITCHES NORMALLY OPEN
44 KV VALLEYFIELD
2.3-KV CONSTRUCTION
3,000-KVA 3 SINGLE-PHASE TRANSFORMERS
TO MONTREAL L. H. & P. CO. SWITCHING STATION
120 KV
46,500 KVA 3 PHASE
44 KV
23,250 KVA 3 PHASE
13.2-KV TRANSFER BUS
13.2 KV
X
7,200-KVA 60-CYCLE GENERATORS
A
B
1
2
3
4
5
6
7
8
9
10
11
12
13
14
46,625-KVA 60-CYCLE GENERATORS
TO HYDRO-ELECTRIC POWER COMMISSION SYSTEM
220-KV LINE
220 KV
87,750-KVA BANK 3 SINGLE-PHASE 29,250-KVA TRANSFORMERS
13.2-KV TRANSFER BUS
13.2 KV
43,882-KVA 25-CYCLE GENERATORS
13.2 KV
STATION AUX. 550 VOLTS
AUX. 1 & 2 550 VOLTS
1,350 KVA 3 PHASE
13.2-KV STATION SERVICE
AUX. 9 & 10 550 VOLTS
1350 KVA 3 PHASE
13.2-KV EMERGENCY BUS

Schematic Wiring Diagram for Two Auxiliary and Ten Main Generating Units age windings each of $^1/_2$ rated transformer capacity; that is, the bank has 2 independent low voltage Δ-connected windings each of which is connected to an independent generator. As the reactance between these two Δ's is high (55 per cent based upon rated transformer kva) the short circuit stresses on generator windings and buses, generator breaker duty, etc., are reduced materially. The high voltage windings are provided with full capacity taps 5 per cent above and below the rated voltage of 218 kv. Core and coils were shipped assembled (except for some of the coil end insulation) in nitrogen in a special shipping tank. The transformer tanks, which are 13 ft $2^3/_4$ in. in diameter, were shipped in three sections. The complete transformers have a height of 25 ft 3 in. from rail to top of tank and an overall height of 36 ft 2 in. The total net weight per transformer is 415,000 lb, of which 152,000 lb is oil.

Transformers used for delivery of 60-cycle power at 120 kv are water-cooled 3-phase units rated 46,500 kva, 50 deg C rise, 13.2/120 kv; these rated voltages are based upon full rated kva at 85-per cent power factor. The low voltage windings are Δ-connected, and the high voltage windings star-connected; the high voltage windings are provided with 5-per cent full-capacity taps above and below 120 kv. Assembled core and coils were shipped in oil in the lower section of the two-section tank. Transformer tanks are oval 9 ft 3 in. by 17 ft; the transformers have a height of 21 ft from rail to top of tank and an overall height of 27 ft 3 in. The total net weight per transformer is 282,000 lb, of which 109,000 lb is oil.

Transformers used for delivery of 60-cycle power at 44 kv are water-cooled 3-phase units rated 23,250 kva, 50 deg C rise, 13.2/44 kv. The low voltage windings are Δ-connected, and the high voltage windings star-connected; 46- and 48-kv full capacity taps are provided. The voltage ratings are based upon full rated kva at 85-per cent power factor. The general design of these transformers is similar to the design of the 46,500-kva 120-kv transformers but because of their relatively small size it was possible to ship them in their own tanks in oil.

An induced voltage test of 480 kv was specified for the 220-kv transformers, 252 kv for the 120-kv transformers, and 97 kv for the 44-kv transformers. The impulse strength of the 220- and 120-kv transformers is guaranteed to be in excess of line insulation, which consists of, respectively, fourteen and seven 10-in. insulator units, spaced $5^3/_4$ in.

### CIRCUIT BREAKERS

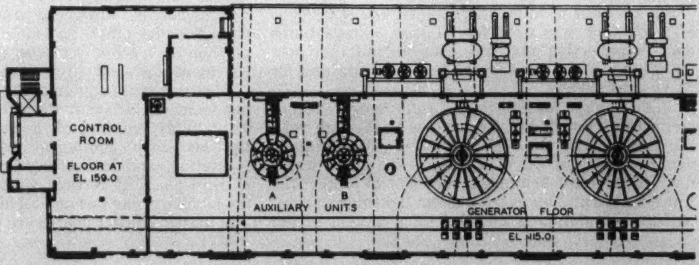
All circuit breakers are designed for an interrupting capacity in excess of estimated maximum requirements. The specified interrupting capacity (*OCO* plus *OCO* basis) is 2,500,000 kva for the 230-kv breakers; 1,500,000 kva for the 138-kv breakers controlling the 120-kv circuits; 1,000,000 kva for the 46-kv breakers; 800,000 kva for the 15-kv generator circuit breakers for generating units Nos. 9 and 10; and 600,000 kva for all other 15-kv station breakers.

The 230- and 138-kv breakers are of the oil blast explosion chamber contact type and are designed for high speed operation, the time from energizing of trip coil to arc extinction being 0.133 sec (8 cycles on a 60-cycle basis). The one-minute voltage test specified on the assembled breakers was 520 and 312 kv, respectively, for the 230- and 138-kv breakers. Impulse strengths of the 230- and 138-kv breakers are guaranteed in excess of the strength of corresponding line insulation, which consists of, respectively, fourteen and seven 10-in. insulator units spaced $5^3/_4$ in.

The 15-kv station breakers meet all A.I.E.E. insulation requirements for 25-kv rating, the one-minute test voltage being 58 kv and the bushing flashover 75 kv. Breakers are designed for high opening and closing speeds, the elapsed time from energizing of closing coil to touching of contacts being 0.35 sec, and the elapsed time from energizing of trip coil to parting of contacts being 0.08 sec. The average breaker speed after parting of contact is approximately 7 ft per second for the 2,400-amp breakers and 11 ft per second for the 600-amp breakers.

### BUS SYSTEMS

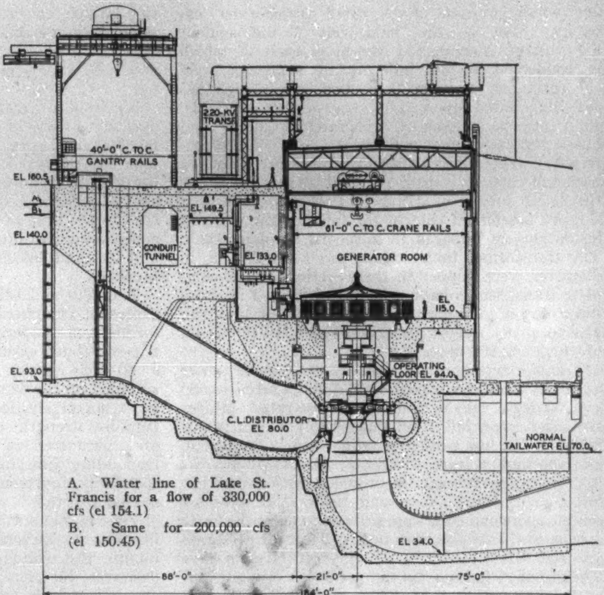
Since the transformers are located on the bulkhead, as mentioned previously, the required low voltage bus length is reduced to a minimum. Except for short sections where bar copper proved the most economic, all 15-kv buses are of tubular section, 3-in. *IPS* (iron pipe size) and $1^1/_2$-in. *IPS* copper tubing being used for the power and auxiliary



SECTIONAL PLAN OF POWER HOUSE FROM EAST END TO AND INCLUDING MAIN GENERATING UNIT NO. 2

buses, respectively. Bus supports have a flashover of 80 kv and a cantilever strength at the bus line in excess of 4,300 lb. With the system layout used mechanical stresses resulting from short circuits are relatively low, the calculated maximum support stress (stress factor times electromagnetic force) being 510 lb. The support bases are provided with a drip-proof feature so that when installed inverted, water leakage through the supporting slab will not cause flashover. Bushings of rather unusual design were required to take the buses through the bulk head slab which is more than 3 ft in thickness.

High voltage breakers for the 120-kv transformers are located on the bulkhead adjacent to the corresponding transformers, the necessary disconnecting switches and bus connections being mounted on steelwork supported by the power house structure. At the downstream line of the power house connection is made to the circuits of the Montreal Light, Heat and Power Consolidated.



A. Water line of Lake St. Francis for a flow of 330,000 cfs (el 154.1)
B. Same for 200,000 cfs (el 150.45)

Typical Transverse Section Through Power House, Showing Details of a Main Generating Unit

From the terminals of the 220-kv transformers connection is made to disconnecting switches supported by steelwork on the power house, and thence through strain buses to a switching station on the downstream side of the power house; there connection is made to outgoing circuits feeding into the Hydro-Electric Power Commission system.

The circuit from the 44-kv transformer passes through disconnecting switches supported by steelwork on the power house structure, thence through a strain bus to a switching station adjacent to the entrance end of the power house. At that point a step-down station is located for local construction equipment and switching is provided for the outgoing 44-kv circuits.

For the sake of interchangeability, the same type of post unit was used for all high voltage buses and disconnecting switches, using six units per post for 220-kv, three units for 120-kv, and one unit for 44-kv equipment.

Spillway gaps for limiting lightning surge voltages are installed on the bus connections to the high voltage terminals of the 220- and 120-kv transformers. Some columns of the steelwork on the power house roof are extended to a height sufficient to protect the transformers and buses from direct lightning strokes. Reduced insulation is installed on a section of the 220-kv line together with a spillway gap on the transmission tower nearest the switching station.

## Control System

Adjacent to each generator on the mezzanine floor (el 133.0) is installed a vertical steel switchboard including the necessary control and indicating equipment for emergency operation of the generator; voltage regulator and rheostats for generator voltage control; protective relays for the generator, step-up transformer, and auxiliary bus section; generator and transformer temperature indicating equipment; the necessary recording instruments for the generator; and the supervisory relays to the master control boards. Adjacent to each generator on the main floor (el 115.0) and mounted on the base supporting the exciter set is a steel pillar containing the generator field circuit breaker and accessories.

Master control equipment is located in the operating room (el 159.0) at the entrance end of the station. This consists of a benchboard containing the necessary equipment for complete control, regulation, and indication of generator output, and a corresponding vertical control board controlling the auxiliary ring bus and all high voltage switching. The master control boards are designed so that they may be expanded as required to take care of additional generating equipment up to the maximum possible installation of 2,000,000 hp. Both generator control and indicating equipment are installed on the sloping benchboard sections (requiring a total width of 8 in. per generator) thus allowing the operators an unobstructed view of the vertical control boards back of the benchboards.

Individual generator switchboards are on a 250-volt d-c control system; by turning a switch they can be cut off from the 48-volt control system and operated independently. All cable connections, control motor-generator sets, and batteries are on a floor directly below the operating floor. This floor connects with the conduit tunnel running the length of the station. All control cable is carried in corrugated metal trays through the tunnel and thence through conduit embedded in the various floors to the required locations.

### Protective Relaying

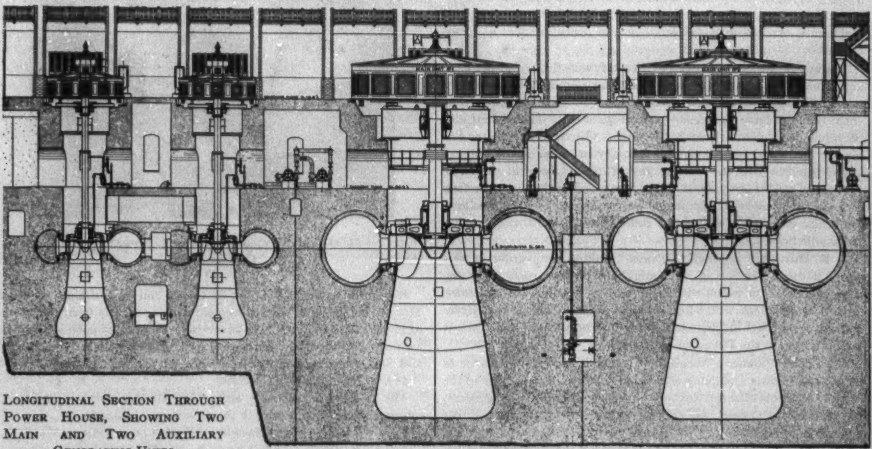
An extensive scheme of protective relaying designed to clear defective equipment in minimum time with the least possible interference with the operation of other equipment is provided. Each major element of station equipment is differentially protected and is provided with adequate back-up protection. To minimize the damage from a generator winding failure, operation of the generator differential relays not only clears the generator and opens the generator field, but also operates a shut-down device for quick closure of the turbine gates. Directional reactance relays together with residual ground relays are used for the 220-kv line protection.

### Station Heating and Ventilating

The generators take cool air (125,000 cu ft per minute for each main unit) through pier openings below the generator floor and discharge the heated air through louvers in the generator frame into the power house from which the heated air escapes through the upper windows on both the upstream and downstream side of the station. To keep the headgates free of ice during the winter months, ducts are provided for diversion of heated air into the housings over the headgate openings. Openings with removable covers are installed in the generator floor to permit any desired amount of recirculation of the air passing through the generators, thus allowing the power house to be kept as warm as desired during the winter months. Electric heating is provided for the service building.

### Comments

The main feature of the development is its simplicity resulting from a combination of favorable topographic factors and uniformity of stream flow. It is strategically located convenient to a great industrial area. Additional installation of station equipment and the corresponding additional water diversion can be made at relatively low cost when and as needed to meet industrial demands. At present about $^{1}/_{2}$ of the mean river flow is unallocated, but prior to complete diversion there must be coöperation with or acquisition of the rights of the three low head hydroelectric plants now operating in this section of the river.



Longitudinal Section Through Power House, Showing Two Main and Two Auxiliary Generating Units

## Discussion

**B. L. Barns:** Because of the location of this station close to a large city and the popular interest in such an immense and important section of the St. Lawrence Waterway development Mr. Lee was justifiably anxious that the long row of generators which will comprise the generator equipment of this station eventually should not resemble the congregations of oil storage tanks one sees in the oil fields. The diameter and height of the generator frames and the lack of any direct-connected exciters to relieve the plainness of the cover might have developed inadvertently into machines of an uninteresting and unimpressive appearance. Therefore, Mr. Lee requested the manufacturer to give particular attention to the architectural appearance of the external surfaces. The construction shown in the various illustrations in Mr. Lee's paper was decided upon after the preparation of numerous drawings and sketches by the factory draftsmen and outside architects and artists. Finally a full size model in wood and sheet fiber was set up, painted, and photographed in the factory. The final color treatment consisted of a dark green on the body of the frame and aluminum on the lamp pedestal, cover, and stator trim. The whole gives the desired effect of balanced proportions, size, and pleasing appearance.

The main units are of the so-called umbrella type of construction having the main guide bearing and thrust bearing below the rotor, but unlike all or nearly all other vertical generators of this type, these machines are provided with additional guide bearings above the rotors. This upper guide bearing is arranged to lubricate itself in the oil well. The main guide bearing between the rotor and the thrust bearing also is self-lubricating, thus making it unnecessary to provide external means of oil circulation for the operation of the machines. The main guide bearings and thrust bearings are divided into segments suitable for shifting with light tackle into position for handling, with the power house cranes, through openings in the cover and rotating structures.

Indicating thermometers for the bearings, flow indicators for the bearing cool water, and bearing oil level indicators are mounted on steel panels in the face of the generator piers at a convenient height from the floor at elevation 94.0. In recesses back of these panels are pipe connections for filling or draining the oil wells. The collector rings and brushes are accessible for inspection from a platform below the thrust bearing supporting bridge or bracket. This platform is reached by a stairway from the operating floor at elevation 94.0.

The hub of the rotor is keyed to the shaft with 2 Lewis keys; each key is made up of two tapered pieces that permit it to be readily loosened and removed. The hub is bored in such a manner that when the keys have been removed it is quite loose on the shaft and the whole rotor can be quickly lifted off. Conversely the rotor can readily be placed on the shaft. The thrust collar and shaft are keyed together with an annular key fitting a groove in the shaft so that the weight of the shaft will be supported on the thrust bearing if the rotor is removed. In assembling or dismantling the machine, the bridge or bracket with shaft, guide bearing, and thrust bearing are handled as a unit.

**J. R. Dunbar:** Perhaps the most striking innovation in this power house is the use of the umbrella type construction for the large generators in which the thrust bearing is below the generator rotor. As far as the writer knows this is the first time this construction has been used in Eastern Canada and only the second time it has been used in the Dominion of Canada.

The earlier Canadian installation is the Ruskin development of the Western Power Company of Canada, Limited, a subsidiary of the British Columbia Electric Railway Company. The Ruskin generating unit is a 120-rpm, 44,000-kva, 13,800-volt generator, direct connected to a 42,500-hp turbine. A cross section through the generator itself is shown in Fig. 1. It is seen that the construction in this case is very similar to that used for the Beauharnois generators. In both cases there is no heavy bracket above the generator stator, the only structure above the generator being a light covering. In the case of the Ruskin generators this cover had to support the stator of the direct connected exciter. The heavy bracket is located below the rotor in each case and carries the large thrust bearing that supports the weight of the generator, the turbine rotors, and the unbalanced water thrust.

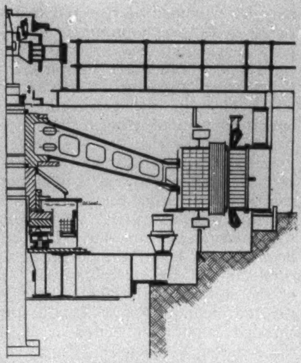


Fig. 1—Section Through 44,000-Kva Umbrella Type Generator

A view of the installed Ruskin generator shortly before construction was completed is shown in Fig. 2. A comparison of this installation with the installed view of the Beauharnois generators shows that the umbrella type of construction produces generators whose appearance differs considerably from the usual appearance when the thrust bearing is located above the rotor, but which nevertheless is quite pleasing.

The 29,250 kva, 25-cycle transformers physically are the largest units in operation in Canada and undoubtedly are the largest that have been shipped in nitrogen. As far as the writer knows this is the first installation in Canada which has made use of 2 individual low voltage windings, to each of which is connected 1 generator. This construction is very common in the United States but so far has not yet been generally adopted in Canada.

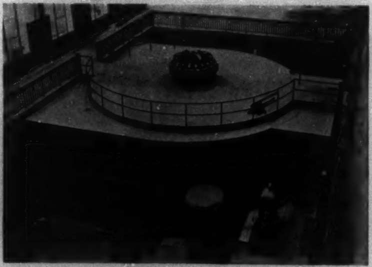


Fig. 2—44,000-Kva Umbrella Type Generator for Ruskin Development

Reference might also be made to the coil end insulation which Mr. Lee mentions as having been shipped separately from the transformers. The portion of the insulation that was shipped separately formed part of the barriers between the high and low tension groups and also was used to support certain of the insulating structures that were located above the coils.

The 46,500-kva, 60-cycle units have the highest kva rating of any transformers in service in the Dominion of Canada.

**J. G. Glassco:** It is somewhat difficult to comment on Mr. W. S. Lee's paper without a first-hand knowledge of the hydraulic and electrical problems involved in a development of this magnitude. The difficulty of determining exactly the time and operating conditions for each successive stage of development makes the policy of step by step construction one of paramount importance. Any other method adopted with the intention of lowering the ultimate capital cost would be a financial speculation carrying too great a risk, especially in a territory where such a large percentage of the energy now being developed is sold in thermal competition with coal.

Engineers should be interested in the simplicity of the general layout and the apparent lack of complicated operating arrangements in spite of the enormous amount of energy to be handled. Although unavoidable, it seems most unfortunate that our major Canadian hydroelectric plant should have been burdened with production at two different frequencies. One cannot help but contemplate the possibility of two great systems in Quebec and Ontario being tied together ultimately through frequency changers, thus permitting the standardization of generator frequencies.

The superstructure of the power house is a good example of the tendency to use brick for the purpose of obtaining not only an economical building material, but one which lends itself to satisfactory architectural treatment and convenience in the progress schedule of the work. The writer is curious, however, to know what method was used to take care of the contraction problem at the point where the brick superstructure bridges over the contraction joints in the concrete substructure. An effort was made in a similar design of the Slave Falls plant in Manitoba to prevent unsightly temperature cracks in the brick superstructure, without the use of vertical contraction joints in the brick work. While not entirely successful, the slight cracks that did develop are very difficult to observe.

The addition of such a large quantity of power in Quebec and Ontario markets as contemplated by the ultimate development of 2,000,000 horse power at Beauharnois is quite a strain on the imagination, and particularly so, when the total cost is carried right to the point of the commercial and domestic customers' meters. Unless there be an industrial expansion and increase in population far beyond that which can reasonably be anticipated at the present time, there hardly seems to be justification in making any extension until the slack is taken up at the other plants in the two provinces and most of the electric boiler energy diverted back to its normal channel. It would be a pity if contractual obligations were carried out with no consideration for economic necessity resulting inevitably in harm to the electrical industry and serious financial loss to the people as a whole. It is easy to understand the natural desire to seek a solution in the export of power as a temporary expedient, but there can be little doubt that the establishment of cheap power for industrial use in territory adjacent to Quebec and Ontario will act as a serious handicap in the creation of industries in Canada.

**Claude Gliddon:** An important problem in the layout of such a large station appears to be the elimination of vital points or bottle necks where trouble may cripple the whole station. In this regard the unit system for auxiliaries and the control seems to have been followed out rather than a centralized system. There are, however, a few points on which it would be interesting to have some further information, such as:

1. There appear to be only 2 pumps for supplying cooling water to the transformers, which would indicate that the whole station output is dependent on the functioning of these pumps. Are there any special provisions made in this regard?

2. It is noted that the auxiliary bus runs the whole length of the station and that the bus work is of more or less open type construction. A fault on this bus would appear to be quite serious. What precautions are taken to prevent accidental contact with this bus and to ensure proper relaying of any affected section? There are a large number of disconnects on this bus. Are interlocks provided to prevent paralleling 60-cycle units through disconnects on the transfer bus?

3. It is noted that two generating units can be operated as a separate and independent station. This is with the exception of excitation which depends on service from the auxiliary bus. Could not a satisfactory speed of excitation be obtained with a direct connected exciter with subexciter?

4. Has any provision been made for the prevention and spread of fire and smoke in the very long rooms and galleries?

One of the notable features appears to be the tendency toward outdoor equipment and the elimination of a large generator room. It is assumed that when future extensions are made, that the outdoor trend may have advanced to the point where the generator room building may be dispensed with.

The elimination of large power cables in the station is notable. It is presumed, however, that this limits the generator split phase protection to the windings only. The use of a modified ring bus for the 220-kv switching station, as developed for other similar stations, is noted. This layout appears to be giving satisfactory results at other stations.

The comparatively small rupturing capacity required in the 120-kv oil circuit breakers clearly demonstrates an advantage of generator, transformer, and line unit set-up. It would be interesting to know why a 13-kv transfer bus was adopted rather than, say, a 120-kv transfer bus, which would allow of overloading lines in case of transformer failure.

Why was tubular copper bus used rather than, say, aluminum channel bus which would have permitted longer spans? No mention is made of overhead ground wires in connection with lightning protection of the switching stations. It is noted that the control cables are laid in open trays. Are these control cables lead covered or fabric covered?

Are the generator neutrals grounded, and if so is there a circuit breaker provided in the neutral lead to disconnect the neutral in case of generator ground fault so as to minimize danger of burning on account of the slow rate of decay of generator voltage.

In the use of reactance relays was it felt that the more accurate settings obtainable would offset the advantages of the faster and simpler impedance relays?

The use of the torque motor regulator appears to have removed a serious objection which there is to many regulators that are dependent on the direct current supply for their operation.

**N. E. Funk:** From the standpoint of economic hydroelectric power production on the St. Lawrence River, it would appear that this project should be utilized to its complete capacity before any development at another location is begun. It is quite obvious that the development of other locations for their initial capacity requires, in addition to the building of power plants, the construction of numerous dams, dikes, tail races, and possibly canals; whereas increased capacity at the Beauharnois development may be obtained by extending the existing power house, dredging the existing canal, and excavating additional tail races.

Let us at least be hopeful that the development of the power possibilities of the St. Lawrence River will be based on the sound economics of power production and not made subservient to or by-products of other developments that may be made to appear as having greater national or international political desirability.

**N. B. Higgins:** The paper particularly emphasizes the unusual natural advantages of the Beauharnois project with respect to flow, topography, and geology. The uniformity of the flow of the St. Lawrence river probably is without parallel in any river of its size in the world. The topography of the canal area, and the prevalence of easily dredgeable marine clay, were unusually favorable for the construction of the intake canal, and are especially favorable for the enlargement by dredging of its cross-sectional area as the project is extended. Another favorable factor is the rock ledge on which the power house is built.

Mr. Lee's statement that, "the total (ultimate) capital investment will be as low as if the ultimate installation had been constructed in one operation," stresses one of the most unique features of the project; namely, its easy adaptability to growth step by step, parallel to the increasing load. For a project of the size of Beauharnois, this coordination of installation cost and power demand is important.

Considering the severe winter climate of the St. Lawrence valley, it is noted with interest that at the end of the 15 mile long canal the water reaches the power house intake without passing any provision to skim ice or debris out of the canal. It would be interesting to know if frazil ice is regarded as a problem, and if so what provisions have been made to combat it. A statement of the plant experience in this respect during the past winter, would be most interesting.

The designers have produced a surprisingly simple electrical layout, considering the fact that power is delivered at 2 frequencies and 3 voltages. Economical use has been made of the group and unit system, and skillful advantage taken of high average river flow, block load conditions, interconnections, and equipment reliability to simplify group low tension connections and entirely eliminate connections between groups. It is doubtful if such simplicity could have been achieved with the same voltages and frequencies in a run-of-river plant; a tie probably would have been necessary to permit shifting of output from one group to the other to most efficiently utilize water at times of deficient flow.

The proximity of the Montreal Light Heat and Power Company's lines has reduced to a minimum the switching equipment on these lines at the power station; this, no doubt, has effected an appreciable saving in investment. A simple diagram of the station at the point of interconnection would be of interest.

It is noted that while the unit scheme has been carried through to the excitation system, motor-driven exciters have been used instead of the more simple direct-connected units. It is assumed that this was due to the slow speed of the main units making direct-connected exciters large and the cost of securing satisfactory speed of response high. The use of a portable spare exciter set is in keeping with the simplicity of design followed throughout.

The station service generating system is unique from several angles. Beauharnois, to our knowledge, is the first large generating station to employ 13,200 volts as an auxiliary voltage. This provides economical distribution over the rather long distances involved, and permits direct connection to the transfer bus for emergency supply.

The use of motor-driven exciters places a severe duty on the auxiliary electrical system; this, and the size and importance of the station, have produced a layout of conservative and reliable design.

In many stations, where house units are installed, advantage is taken of the emergency tie to pump surplus power from the station system into the main system. At Safe Harbor, for example, the second, or spare house unit was justified by its ability to "pay its way" by normally adding its output to that of the main system. Units thus operated may be separated from the essential auxiliary supply and yet serve as a running emergency supply. It would be of interest to learn whether it is the designers' plan to operate the Beauharnois system in this manner.

In a station the size of Beauharnois, physical limitations alone preclude the use of a central control board of full size. The designers have taken advantage of the latest developments by the use of a master switchboard, supervising individual full size control boards. This must have resulted in a very large saving in conduit and wire alone. Perhaps the next step will be the elimination of the individual unit controls and the use of direct miniature control, the relays, recorders, etc., of course, remaining near the units.

The author states that the transformer temperature indicating equipment, recording instruments, and certain meters are located at the generator local boards. Are these also supervised and transmitted to the control room, or is there an attendant present on the el-133 floor to read these meters?

In regard to the auxiliary mechanical equipment, the Beauharnois station is interesting in that practically all of this type of equipment is located on an operating floor below the generator floor. This arrangement of governor actuators and accumulator tanks at this lower elevation, with short pressure lines from the accumulator tanks to the turbine gates operating cylinders, provides for quick response of the turbine gates to the movements of the governor valve, an obvious operating advantage, as well as economy in cost.

The author states that all of the governor equipment is located on floor, el-94.0. Does this mean that the sump tanks are placed at this same elevation, and if so what provision is made for draining the governor system? It would be interesting to know which type of fluid is used in the governor system, and the reasons for its selection.

**W. S. Lee:** In our engineering experience we have found that simplicity of layout, coordination of effort, and 100 per cent cooperation by all interested are absolutely essential successfully to put through a project of the magnitude of the Beauharnois development with a minimum of expenditure and a maximum of benefit. The design was very carefully studied to permit low cost of step-by-step construction, and at the same time provide the requisite flexibility for changes and improvements in equipment design, and revision of future power requirements.

Mr. Glassco regrets that this station should have been burdened with production at 2 different frequencies. While a single generating frequency ordinarily would be advantageous, it imposed no particular handicap in this case, as, in any event, the various generator groups could and probably would be operated independently. In fact, from the generation and transmission standpoint the present set-up of 60 cycles for the nearby industrial area and 25 cycles for the longer transmission of power into Ontario district is economical. A careful study of methods and designs was developed, whereby, if future conditions require, a 60- and a 25-cycle generator (each of full rating) driven by a single turbine can be installed in the space allotted to each of the present units. Not only will this serve to reduce the number of spare units for both frequencies, but will permit of some interchange of power and regulation between the 25- and 60-cycle power systems.

Regarding Mr. Glassco's question about construction of the brick superstructure, we considered installing hidden expansion joints in the brick pilasters adjacent to the substructure expansion joints, but after an examination of the Isle Maligne Station, which is of similar construction without expansion joints in the brickwork, we decided to omit these joints. While a few cracks have developed, they are scarcely visible and are minor in character.

With reference to Mr. Gliddon's discussion, the two cooling water pumps are fed from service transformers connected to independent sections of the auxiliary ring bus, each pump being of ample capacity for all the present installed transformers. For the complete transformer installation for the first powerhouse section, 4 pumps each fed from a different bus section, will be installed. Differential relaying is provided for each ring bus section and its service transformer bank, consequently a fault will be localized to a maximum of two units. Disconnects are provided only for emergency transfer of a service transformer bank in the event of its bus section fault. It will be noted that the ring bus is fed at 3 points, 2 being from the station units and the third being from the 60-cycle power transfer bus. This third connection is carried by cable in conduit through the conduit tunnel to the extreme end of the ring bus so that failure of 2 ring sections will not cut off the auxiliary supply for a number of units.

As a very complete relaying system was installed to insure isolation of defective equipment and as the apparatus is so widely spaced as to prevent spread of flames, no fire walls or baffles were considered necessary. Provision is made for circuit breakers in the generator neutrals if found desirable; the generator protective layout provides means, in the event of a winding failure, for isolation of the generator and for immediate closure of the turbine gates thus bringing the rotor to a standstill in the minimum of time. The 13-kv power busses are for transfer purposes only, and are not used to parallel generators. The 120-kv bus layout is owned by the Montreal Light, Heat and Power Company and is not a part of the station. Ground conductors are installed over the 220-kv switching station. All control cables are lead covered.

Regarding the excitation system as commented upon by both Mr. Gliddon and Mr. Higgins, every precaution was taken to provide uninterrupted power supply for the exciter sets. It was found that adequate response rates and stability could not be secured with direct connected exciters but could be secured with exciter sets provided the power supply was taken from an independent and unaffected power source. This was accomplished by providing duplicate station service units having direct connected exciters feeding into the auxiliary ring bus which, together with the connection from the 60-cycle power transfer bus, provides 3 dependable power sources for the exciter sets and for the other station auxiliaries. The 220-kv system always will have independent power source for driving its generator exciters. On account of slow speed of turbines, direct connected exciters were more costly.

Concerning ice conditions: the Beauharnois development after winter really sets in, has an ice sheet above it extending to the foot of the Long Sault Rapids, the nearest source of all winter frazil, some 40 odd miles. Lake St. Francis intervenes in this stretch as a storage for frazil and is of ample capacity to store the winter's production of frazil from the Long Sault. The only frazil to be contended with at Beauharnois is that formed on the canal surface for the first few days preceding an ice cover and in the case of stormy weather accompanied by low temperatures preceding an ice cover. The Beauharnois plant has passed through the entire cycle of a year's operation and while of course some frazil was passed, there was not enough of it to cause any interruption or delay. The racks, which are entirely submerged, the top being several feet below the surface of the water, are made in 2 sections, provision being made for rapid raising of the upper sections to pass any frazil ice that may reach the station. The turbine gate openings are so large that frazil ice in great quantities will readily pass through them.

The bus layout is such that either of the station units can supplement the 60-cycle power delivery, but under normal conditions this will not be done. Generator and transformer temperature indicating equipment and certain recording and integrating instruments are located on the elevation-133 floor, readings being taken by a switchboard attendant. The necessary emergency signals for this equiqment are located in the main control room.

The governor sump tanks are located in pockets in the elevation-94 floor to provide gravity drainage. Based on our previous experience, oil was considered the most suitable fluid for the governor system.

# Improvements at Burlington Generating Station

BY WALKER L. CISLER* and WALTER P. GAVIT†

Nonmember Nonmember

THE recent development at Burlington generating station of Public Service Electric and Gas Company of New Jersey is of special interest in these days of stringent economies and efforts to make existing equipment go as far as possible. The station contained 3 12,500-kw turbine-generators from 10 to 16 years old with a stoker fired boiler plant all operating at 200 lb steam pressure with 150 deg superheat. The fuel consumption was 22,000 to 25,000 Btu per kwhr which is about what would be expected with these steam conditions and equipment of that period.

The installation of a high pressure pulverized fuel fired boiler and an 18,000-kw high back pressure noncondensing turbine reduced the station heat rate to about 15,000 Btu per kwhr. As a consequence of this improved economy the Burlington generating station is now prime base load capacity and may be expected to continue in this classification for some years to come.

An unfortunate accident that occurred in January 1933 damaged the turbine beyond repair and until the new turbine is completed the old units are being supplied with steam through a reducing valve from the new boiler.

### PLANS FOR DEVELOPMENT OF STATION

The general development of the generation and distribution systems of Public Service Electric and Gas Company will require the location of additional generating capacity in the district served by Burlington generating station and tentative plans were formulated for the extension of this plant. The first step of the extension was to consist of 2 high pressure 75,000-kw turbine-generators with 4 boilers of such a capacity that 3 could produce sufficient steam to operate the 2 turbines.

The load conditions existing at the time these plans were formulated indicated that the extension would not be necessary until some time later. However a capacity contract for the supply of energy from a source outside the Public Service system was to expire at the end of 1931 and the provision of efficient capacity in the Burlington station was desirable as it would obviate the necessity of renewing this contract.

Studies indicated that the efficiency of the Burlington station as a whole could be raised to a satisfactory value by superimposing a high pressure turbine-generator upon the existing 200-lb system. Sufficient steam for the operation of the station with such a high pressure unit could be supplied by one high pressure boiler of the size and type contemplated for the future extension. If this installation were made the old turbine-generators would remain an economical part of the station after the proposed future extension was completed as they could be operated whenever the excess or spare boiler capacity was available. With modern steam generating equipment the time out for maintenance is small so that this excess boiler capacity would normally be available most of the time.

With these several factors in mind it was decided to install one 30,300-sq ft boiler designed for operation with a drum pressure of 730 lb per sq in. gage and a total steam temperature of 850 deg F. A pressure higher than 730 lb per sq in. was not adopted for 2 main reasons. It was desired to avoid the added equipment and operating complications of a reheat cycle. Also 730 lb was the maximum for riveted construction without going to special or expensive design as welded drum construction had not been approved by the code of the American Society of Mechanical Engineers at the time the boilers were under consideration.

Along with this boiler a turbine-generator was installed of 18,000-kw capacity designed for a throttle pressure of 650 lb per sq in. and a total steam temperature of 875 deg F. The turbine was designed to exhaust at a maximum pressure of 205 lb per sq in. into a header system from which the old turbines are supplied. The boiler is capable of producing and the turbine can pass sufficient steam to operate the 3 old turbines at full load. A plan of the present and proposed Burlington station is shown in Fig. 1.

This program provided 18,000 kw of new capacity and brought the old turbines into efficient use without the expense of any boiler capacity in excess of that which would be required for the future 2-unit extension.

### HEAT BALANCE ARRANGEMENT

A heat balance arrangement was devised which took the fullest practical advantage of the possibilities of the existing equipment. A diagram of the operating heat balance is shown in Fig. 2. The proposed arrangement included a 3-stage regenerative feed heating system and an evaporator for make-up. The low pressure heater is supplied with steam bled from the 2 newest of the old turbines. The pressure at the lower bleed point of the oldest of the 3 original units does not correspond to that of the other 2 because of a difference in design. It therefore was not practical to interconnect the lower bleed points of all 3 units.

The intermediate and deaerating heaters are supplied with steam bled into a common header from the upper bleed point of all 3 old turbines. The high pressure heater receives its steam from the ex-

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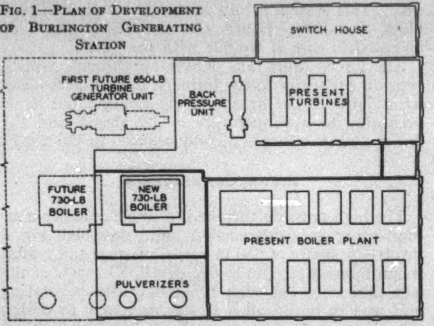
haust of the high pressure unit. The lower bleed point on the old machine was used to extract steam for a make-up evaporator.

For the loads at which the station was expected to operate, a heat rate of about 15,000 Btu per kwhr delivered to the outgoing lines was expected. This represents an improvement over the old station of 32 to 40 per cent. An additional saving in operating labor and maintenance costs was expected as a result of shutting down the old boiler plant. The results attained in actual operation fully bear out predictions as to performance.

FIG. 1—PLAN OF DEVELOPMENT OF BURLINGTON GENERATING STATION


SWITCH HOUSE
FIRST FUTURE 650-LB TURBINE GENERATOR UNIT
BACK PRESSURE UNIT
PRESENT TURBINES
FUTURE 730-LB BOILER
NEW 730-LB BOILER
PRESENT BOILER PLANT
PULVERIZERS

## BOILER, FURNACE, AND SUPERHEATER

A crossdrum straight tube type boiler was chosen as offering the least expensive design for the pressure decided upon. To have adopted the bent tube type would have meant very special design or (at that time) the use of forged drums. A high boiler with air preheater was used as giving greater simplicity and fewer kinds of equipment than a low boiler with economizer and air heater. An overall boiler efficiency of about 85 per cent was used as basis of design.

The furnace has water walls on the 2 sides and rear and on the part of the front wall above the burners. The whole unit is steel encased and insulated with the casing so placed that all water wall and bottom screen downcomers and connections from drum to superheater headers are within the casing. This arrangement avoids the necessity of insulating all these pipes, improves the appearance of the unit as a whole, and makes it cleaner owing to the absence of a multiplicity of external pipes to collect dust.

The superheater is of the multi-loop bare tube type and contains approximately 9,200 sq ft of effective surface. Various types of superheater were considered in selecting this design and arrangement. A straight parallel flow design would not give the desired final steam temperature. A combination part parallel and part counter current design would give a satisfactory superheat curve but was expensive and complicated in design. A straight counter current design was finally selected as combining economy of cost, simplicity of design, and satisfactory performance characteristics.

Each superheater element consists of $6^1/_2$ return bends, the upper $5^1/_2$ of which are of ordinary mild steel, and the lower of chrome vanadium steel. It might have been desirable to make a greater proportion of the tubes of alloy steel, but the maximum one piece length of alloy tubing obtainable was only sufficient for one loop. No satisfactory method for welding 2 pieces of alloy steel was known, though it could satisfactorily be welded to the ordinary steel. Recently the alloy steel has been made in longer pieces and replacement elements have a loop and a half of this material. However, nothing has occurred in operation that would indicate that the additional length of alloy steel was essential.

## PULVERIZED FUEL SYSTEM

Pulverized fuel firing was selected partly because the designers felt that units of such size are more suited to pulverized fuel firing than to stokers and partly because of the flexibility of the pulverized fuel furnace in the matter of burning fuels of widely varying characteristics.

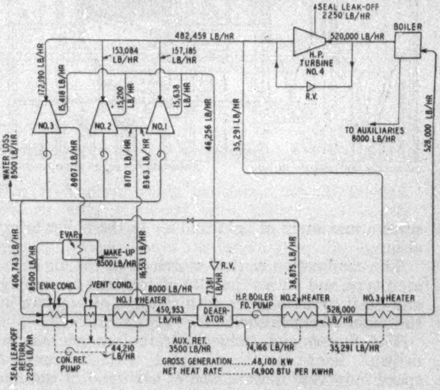

SEAL LEAK-OFF 2250 LB/HR
BOILER
482,459 LB/HR
520,000 LB/HR
H.P. TURBINE NO. 4
R.V.
153,084 LB/HR
157,185 LB/HR
172,190 LB/HR
15,418 LB/HR
15,200 LB/HR
15,638 LB/HR
NO. 3
NO. 2
NO. 1
46,256 LB/HR
35,291 LB/HR
TO AUXILIARIES 8000 LB/HR
528,000 LB/HR
WATER LOSS 8500 LB/HR
8907 LB/HR
8170 LB/HR
8363 LB/HR
406,743 LB/HR
8500 LB/HR
EVAP.
MAKE-UP 8500 LB/HR
16,553 LB/HR
R.V.
7381 LB/HR
38,875 LB/HR
EVAP. COND.
VENT COND.
8000 LB/HR
NO. 1 HEATER
450,953 LB/HR
DEAERATOR
H.P. BOILER FD. PUMP
NO. 2 HEATER
528,000 LB/HR
NO. 3 HEATER
SEAL LEAK-OFF RETURN 2250 LB/HR
CON. RET. PUMP
44,210 LB/HR
AUX. RET. 3500 LB/HR
74,166 LB/HR
35,291 LB/HR
GROSS GENERATION.......48,100 KW
NET HEAT RATE.........14,900 BTU PER KWHR

FIG. 2—HEAT BALANCE FLOW DIAGRAM OF BURLINGTON GENERATING STATION

The design of the pulverized fuel system combines as far as possible the advantages of the storage system with its close control and greater flexibility with the compactness and straightforwardness of the direct system. Bins and feeders are interposed between the mills and burners to assure continuity of rating on the boiler during temporary stoppage of the pulverizing equipment. As will be noted from inspection of the boiler room cross section, Fig. 3, the raw coal bunker, mills, primary air fans, separators, pulverized fuel bin and feeders are compactly arranged in a low section of the building. The burner pipes extend from the feeders up to 8 30-in. horizontal burners. This arrangement assures a maximum of light and air to the boiler firing aisle.

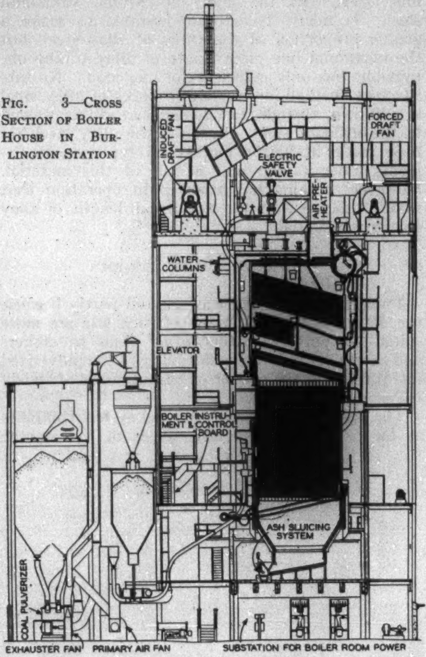


Fig. 3—Cross Section of Boiler House in Burlington Station

The combustion control system is of the air actuated type and varies the rate of coal and air supply and draft in accordance with changes of pressure in the main steam header.

The forced and induced draft fans are motor driven. Each fan is provided with 2 constant speed induction motors, one at each end of the fan shaft. One of the motors is of size and speed suitable for operation of the fan at maximum load while the other smaller motor is of size and speed suitable for operation up to about $^2/_3$ maximum load. The fans run at constant speed, and regulation of the quantity of air or gas delivered at either high or low speed is by manipulation of the inlet vanes on the fans.

In selecting this drive system, 5 arrangements were considered:

1. Two constant speed motors with vane control.
2. Two constant speed motors with damper control.
3. One 2-winding constant speed motor with vane control.
4. One 2-winding constant speed motor with damper control.
5. Two variable speed motors.

The arrangement with 2 constant speed motors and vane control was found to be the most economical. This system is also relatively simple and provides 2 motors, either one of which may be operated in case of trouble with the other.

The forced draft fans deliver air through a plate type air preheater to the burners, mills, and feeders. At 525,000 lb per hr actual evaporation the air is preheated to a temperature of 498 deg F and the flue gas temperature is thereby reduced to 456 deg F.

## Steam Connections

The high pressure turbine is a single-cylinder noncondensing straight-reaction unit designed for a throttle pressure of 650 lb per sq in. gage and a total steam temperature up to 875 deg F. In view of the fact that only one high pressure steam generating unit was to be installed it was necessary to design the steam system so that the 3 existing turbines could be operated on the old boilers in case the high pressure boiler should be out of service. Some consideration was given a scheme of carrying a constant back pressure on the new high pressure turbine so that no changes would have to be made to the old low pressure units. This was discarded in favor of a varying back pressure because of better overall economy. The only change to the 3 old turbines was the substitution of new nozzles for the inlet steam and increased clearances.

Under normal operation the high pressure unit and the 3 low pressure units run as a compound turbine, control being entirely by the high pressure turbine governor. The generators of the 4 elements are tied together electrically and the governors on the 3 low pressure units are wide open. With this arrangement the exhaust pressure from the high pressure unit and consequently the inlet pressure to low pressure machines varies with the load.

The auxiliaries in the old station were mainly steam driven and the question arose as to the economical disposition of the exhaust from these auxiliaries with the regenerative cycle proposed for the new installation. Studies made to determine the economic value of substituting motor drives for the existing steam drives indicated a fuel saving sufficient to make such a change profitable and most of the station auxiliaries, therefore, were motorized.

The governing system and valve arrangements are such that anything but an extraordinary disturbance of the system is taken care of automatically. If one of the generators should be disconnected from the load all the steam from the high pressure unit would tend to pass through the remaining 2 low pressure turbines. These 2 generators would as a consequence advance in phase and momentarily take an overload. At the same time the pressure at the high pressure turbine exhaust would rise sharply. This unit is provided with a device to limit the exhaust pressure to 205 lb. The rise in exhaust pressure would cause this device to function and reduce the flow of steam to the high pressure unit, thus restoring the system to equilibrium.

A by-pass with automatic reducing valve and desuperheater is provided between the high and low pressure steam headers. If the high pressure unit should trip out, steam automatically would be passed to the low pressure header through this bypass and operation of the low pressure unit would not be disturbed. This also permits the old units to be operated on steam from the new boiler during periods when the high pressure turbine is out of service, thus allowing advantage to be taken of the higher efficiency of the new boiler.

### Electrical Connections

The station is connected to the Public Service Electric and Gas Company's transmission system at both Camden and Trenton, as indicated on the diagram of Fig. 4. It also is connected at both these points to the Philadelphia Electric Company's system.

The addition of 22,500 kva to the station capacity and the changes made in circuits connecting the station to the Public Service system, brought about a condition for which the rupturing capacity of all main circuit breakers was inadequate. In order to avoid complete replacement of these circuit breakers with building changes which would be difficult to make, steps were taken to increase the rupturing capacity of the existing equipment. This increase was accomplished by changing the system of connections, introducing reactors, and making certain changes to the breakers themselves.

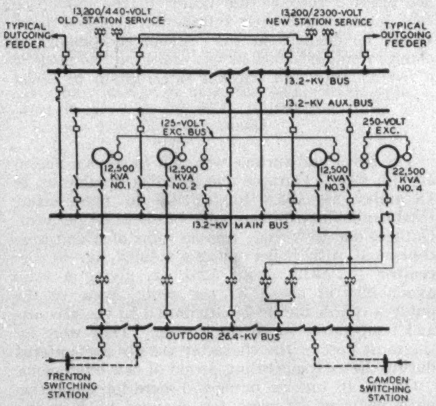

TYPICAL OUTGOING FEEDER
13,200/440-VOLT OLD STATION SERVICE
13,200/2300-VOLT NEW STATION SERVICE
TYPICAL OUTGOING FEEDER
13.2-KV BUS
13.2-KV AUX. BUS
125-VOLT EXC. BUS
250-VOLT EXC.
12,500 KVA NO. 1
12,500 KVA NO. 2
12,500 KVA NO. 3
22,500 KVA NO. 4
13.2-KV MAIN BUS
OUTDOOR 26.4-KV BUS
TRENTON SWITCHING STATION
CAMDEN SWITCHING STATION

Fig. 4—Single Line Diagram of Electrical Connections

With these changes, it was necessary to purchase new breakers only for connections to the new main or synchronizing bus. These circuit breakers are of 1,000,000-kva rupturing capacity. All 26,000-volt breakers were equipped with deion grids which appreciably increase their rupturing capacity. The physical arrangement of the indoor switching equipment with the new breakers and new bus on the first 2 floors is shown in Fig. 5.

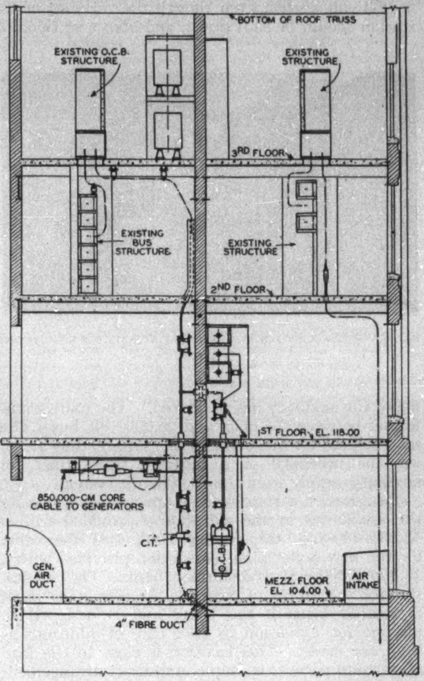

BOTTOM OF ROOF TRUSS
EXISTING O.C.B. STRUCTURE
EXISTING STRUCTURE
3RD FLOOR
EXISTING BUS STRUCTURE
EXISTING STRUCTURE
2ND FLOOR
1ST FLOOR, EL. 118.00
850,000-CM CORE CABLE TO GENERATORS
C.T.
O.C.B.
GEN. AIR DUCT
MEZZ. FLOOR EL. 104.00
AIR INTAKE
4" FIBRE DUCT

Fig. 5—Physical Arrangement of Indoor Bus Structure

With the new system of connections, each generator is connected to the 26,000-volt bus through its own transformer or group of transformers, but, in addition, the generators are paralleled on the 13,000-volt side through the synchronizing bus, and normally remain connected to it. This arrangement permits the 26,000-volt bus to be sectionalized as desired. Normally the Camden section of the system is connected to one bus section and the Trenton to the other. This ties the 2 sections together through 2 transformer groups in series, permitting the shifting of transformers between the Trenton and Camden bus sections as desired. The outdoor switching station is shown in Fig. 6.

The station auxiliaries are supplied from a 13,200-

volt auxiliary bus. This bus is fed through 2 connections to the main or synchronizing bus and one connection to the 26,000-volt outdoor bus. This permits operation of the auxiliary bus from the 26,000-volt system even though the turbines in the station should be shut down, and allows sectionalizing of the auxiliary bus as desired. The spare transformer between the main and 26,000-volt buses also may be used for the auxiliary bus supply, thus avoiding the necessity of a separate transformer for auxiliary supply from the 26,000-volt system.

Fig. 6—Outdoor Switching Station at Burlington Generating Station

Two station service feeders are provided, one for the auxiliaries in the old station provided with a 13,200/440-volt transformer bank and the other for the new boiler plant substation provided with a 13,200/2,300-volt transformer bank. The substation for the supply of power to the new boiler plant is located beneath the latter and is designed to provide for extension to take care of additions as they are made. This location is close to the load center and permits a simple and direct arrangement of feeders to the various motors.

Excitation of the old units was by separate turbine-driven 125-volt generators. The elimination of steam auxiliaries previously discussed included these exciters and they were replaced with new shaft-end generators on the main generators. An emergency exciter bus is energized from a motor driven generator. The new unit is provided with a 250-volt shaft-end exciter and a motor-driven emergency exciter which will be connected to the emergency exciter bus of the future extensions.

## Welded Pipe Joints Used

One of the interesting features of this installation is the fact that, as far as was practical, pipe joints were welded. Flanged joints were used only for connections to large valves and where joints must be broken frequently.

This is the first high pressure power plant in which welding for pipe joints was used throughout to such a large extent. As many welded sections as possible were made in the fabricator's shop, by the electric arc weld process using coated rod. The extent to which shop welding could be used was of course limited by the size of pipe sections that could be shipped to the job. Field welds were made by the oxyacetylene process and all high pressure pipe welds were locally annealed after completion. The valves in the larger lines were flanged but many smaller valves were welded directly to the pipe.

The annealing of the large pipe welds presented a problem for which no equipment was available. A portable box was made up of steel plate lined with asbestos which could be placed over the joint. With the box in place the joint was heated to the desired temperature with oil torches after which the box was packed tight with asbestos and the pipe permitted to cool. All field welds were tested after completion by applying hydrostatic pressure of 1,500 lb per sq in., and hammering with a heavy sledge. No failure of welds has been experienced to date.

## Oil Burner System Added

Shortly after the new installation was put in service the price of fuel oil receded to a low level. Studies indicated that its use in place of coal would result in a material saving in operating cost even after deducting fixed charges which included a high amortization on the installation cost of the necessary oil equipment.

A fuel oil storage, handling, and burning system was installed comprising a 20,000-bbl tank, an unloading wharf at the river, and the necessary pumping, heating, and burning equipment. Oil burners are inserted through the center of the pulverized coal burners and their installation required practically no changes in the original equipment. A change from oil to coal or vice versa may be made in a few minutes and without interruption to boiler operation.

## Operation

The boiler and turbine were put in service February 17, 1932. Outages due to boiler trouble up to December 24, 1932, totaled 917 hr representing total availability for the boiler of about 88 per cent. Outages due to turbine trouble some of which were coincident with boiler outages totaled, up to December 15, 1932, about 1281 hr, giving a total availability of about 82 per cent. None of the outages can definitely be attributed to the pressure and temperature or to the system. They were for the most part of the character usually encountered during the early operating period of new equipment.

Of the 10 turbine outages 5 were for inspection or adjustment, 3 were for changes to bearings, 1 was to determine the cause of a trip-out and 1 was to increase shroud clearance. On December 15th the turbine was shut down to permit installing new end tightening on the shroud bands and a new design of high pressure dummy packing. At the same time some changes were made in the admission valve flanges and bolting to improve the expansion stress distribution.

The turbine was returned to service early in January, 1933, but a few days later was wrecked due to some internal failure the exact nature of which has not been determined. The vibration accompanying the turbine trouble caused the breakage of one of the oil lines to the valve operating gear on top of the turbine. The leaking oil caught fire resulting in a quite serious but localized conflagration. The resulting damage was confined to the turbine and objects near by. Neither the generator of the new unit nor any of the other units in the station was damaged other than by smoke. The station is now operating on steam from the new boiler through a reducing valve and desuperheater.

Operation of the plant aside from the accident to the turbine has been satisfactory. There has been some corrosion in the superheater tubes, and a few superheater tube leaks have occurred due to incomplete welding of return bends.

The turbine was opened up for inspection early in August, 1932, and a heavy gray deposit was found on the blades from the 12th row down to the exhaust, increasing in quantity toward the exhaust end with the last 2 rows comparatively free. This deposit, of course, is carried over from the boiler and through the superheater and consists of the materials used for treatment of the boiler feed water. Elimination of this fouling on turbine blading is one of the problems that must be solved in connection with high pressure and temperature installations. At Burlington the deposited material is very soluble and easily removed by washing with water. However, the turbine must be cooled down considerably before water can be introduced and considerable operating time must be sacrificed.

The station has carried a maximum load of about 53,000 kw with a total steam generation of 625,000 lb per hr, and when fouling of the turbine can be overcome a load at or near this value can be carried continuously with oil fuel. With coal firing the maximum load carried was 51,500 kw with a total steam generation of 550,000 lb per hr. The higher water rate with oil firing is due to a combination of the following circumstances: (1) higher temperature circulating water at the time the above record was made; (2) fouling of turbine blades as previously described herein; (3) some steam leakages that developed within the turbine. The boiler operated continuously from August 13 to December 24, 1932, and during this period produced 1,373 million lb of steam. This is an average of about 429,000 lb per hr.

## Discussion

**T. E. Purcell:** The physical arrangement of the plant presents some ideas that have not been commonly used heretofore. The arrangement of the raw coal bunker and coal preparation plant at a low elevation at one side of the boiler room is good. It is not possible, however, to determine from the written matter or from the cross-section of the boiler house, the reason for locating the boiler room substation underneath the boiler. Placing this substation in some other location, lowering the boiler, and reducing the height of the building would, it seems, save considerable of the cost.

It is explained that a cross drum type boiler was chosen due to pressure limitations on the vertical type at the time the boiler was purchased. An air heater without economizer is used for reduction of stack temperature. It would be interesting to know if this design still would be economical today in comparison with a vertical type boiler with both economizer and air preheater.

The location of water wall and water screen downcomers within the boiler casing is an excellent idea, and should improve the appearance of the boiler room considerably, together with reduction of initial cost and elimination of the cost of cleaning and maintaining the insulation on these pipes.

It is stated in the paper that the steam auxiliaries in the old plant were changed to electric drive as a result of an economic study of the situation. It would be interesting to know the valuation of the various factors entering into this study, especially in view of the difference of opinion among designers concerning the choice of auxiliary drive.

# Obtaining Comfort Conditions by Controlled Radiation From Electrically Heated Walls

BY L. W. SCHAD*

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***Synopsis.***—*At sedentary occupations under normal indoor winter conditions the human body loses heat at the rate of 400 Btu per hour, of which approximately 46 per cent is radiated, 30 per cent is convected, and 24 per cent is lost by the evaporation of moisture from skin and lungs. The skin and clothing surface temperatures average about 80 deg F. With solid surroundings at 80 deg F, therefore, no heat would be lost by radiation. Any intermediate temperature between the normally prevailing inside wall temperature and 80 deg F would mean a corresponding modification in the amount of heat radiated. Compensation for this decrease in radiated heat may be effected by lowering the air temperature. The effect on human comfort of thus controlling the amount of heat radiated from the body is discussed in this paper. The possibility of using electric energy for this application, together with equipment and operating costs, also is discussed.*

A FEW years ago Mr. L. W. Chubb, director of the Westinghouse research laboratories, East Pittsburgh, Pa., suggested the possibility of using electrically heated wall and ceiling areas for creating winter comfort indoors. Based upon his observation of the importance of radiant energy on the human body's sensation of warmth in such instances as sunshine through clear, cold mountainous air, or the flash of radiant energy through a train window from a pile of burning ties, he conceived the idea of making radiation a more important factor in producing comfort conditions. Reducing the idea to practice in occupied space involves the use of large surfaces at relatively low temperatures such as 80 to 120 deg F.

At the research laboratories of the American Society of Heating and Ventilating Engineers it has been found that the average person engaged in ordinary sedentary occupation loses heat at the rate of approximately 400 Btu per hour.[1] This heat is dissipated by radiation, convection, and moisture evaporation from skin and lungs. Mr. L. B. Aldrich[2] has found that in ordinary winter conditions indoors 46 per cent of the body's total waste heat is radiated, 30 per cent is convected, and 24 per cent disappears as latent heat of vaporization.

The body's internal temperature is normally 99 deg F, but the temperature of the outside surfaces of both exposed skin and clothing from which radiation and convection take place is about 80 deg F with variations above and below according to surrounding conditions and clothing worn.

If the walls, ceiling, and floor of a room were at a temperature of 80 deg F, no heat would be lost by radiation from a person within the room. However, health and comfort demand that the heat generated by the ordinary processes of life, which is more or less constant under given conditions, be dissipated; hence, if radiation be prevented, convection or moisture evaporation, or both, must be increased.

It is possible to heat certain portions of solid enclosures so as to obtain partial or entire nullification of body radiation. Under such conditions the room air temperature should be lowered to restore the balance between heat generated in the body and its dissipation.

## Test Equipment

Many combinations of warmed enclosures with varied air temperatures have been investigated in a room (see Fig. 1) especially designed for studying air conditioning problems at the plant of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. This room, with internal dimensions of 12x16x8.8 ft, is built within one of the standard research laboratories rooms so that there is a space between the walls and ceilings of the 2 rooms from 18 to 24 in. in width. This permits a temperature variation in the air surrounding the experimental room as well as ease in making various adjustments in power supply, air flow, etc. Figure 2 shows the heating units used in the wall and ceiling construction; each unit is 4 ft long and $1^1/_2$ ft wide, and was designed for 250 watts at 110 volts. The base of the unit is a standard insulating lath having a thermal conductivity of 0.39 Btu per hour per square foot with a gradient of 1 deg F per inch of thickness. After these units were nailed to the joist and studding, a finish coat of plaster was applied producing a smooth inside surface to which several coats of enamel were applied to prevent air from passing through the walls. All joints and floor cracks were sealed carefully with linoleum cement so that the air supply to and from the room could be accurately controlled and measured.

Air was drawn from outdoors through a duct above the ceiling and distributed in the room by means of the center ceiling duct shown in Fig. 1. This duct, running along the entire length of the ceiling halfway between the sides of the room, delivered cold air laterally, that is, parallel with the ceiling so that the overall effect was a complete diffusion of the incoming air with the air in the room. Exit ducts were placed in the walls near the floor. The air flow was measured carefully both at entrance and exit by means of nozzle and orifice meters, with an inclined draft gage used to indicate equal pressures between inside and outside atmosphere. A centrifugal blower with speed control operating in the entrance duct and a suction fan in the exit

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1. For all references see bibliography.

*Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.*

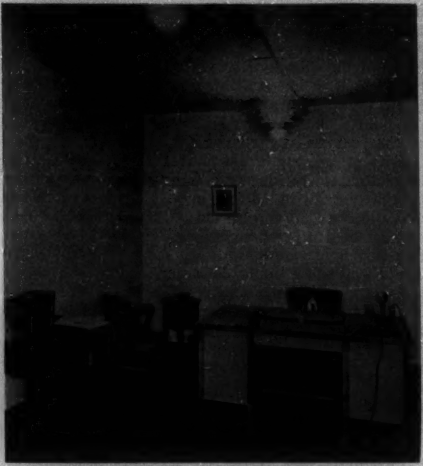


FIG. 1—ONE SIDE OF THE EXPERIMENTAL ROOM IN WHICH THE TESTS WERE MADE

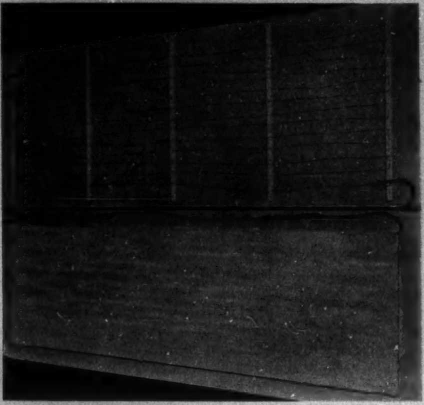


FIG. 2—TWO OF THE ELECTRICALLY HEATED PANELS, THE UPPER ONE BEFORE AND THE LOWER ONE AFTER IMBEDDING THE RESISTANCE WIRES IN PLASTER

duct were so operated as to eliminate pressure differences between the inside and outside atmosphere, thus eliminating as far as possible any air leaks.

Copper-"advance" thermocouples with the warm junction soldered to a patch of copper screen just under the finish coat of plaster were led out along isothermal surfaces to the edges of each heating unit and then back through the wall to a multiple switch and potentiometer. Surface temperatures thus were accurately determined. Air temperatures were determined in the ducts as well as in various parts of the room with No. 36 B&S gage copper-"advance" couples. Mercury thermometers also were used, mainly to see how far their indications deviated from true air temperatures under various conditions of warm walls and cool air.

### TEST PROCEDURE

Preliminary work showed quite definitely that not only can comfort conditions be obtained with 80-deg walls and 60-deg air, but also that such environment is highly invigorating. The cool air is quite acceptable when one at the same time feels entirely comfortable. However, to maintain the air at 60 deg within 80-deg walls, it was necessary to introduce fresh cold air into the room at a rate of from 6 to 10 changes per hour, depending upon the temperature of the air fed into the room. It becomes apparent at once, therefore, that heating enclosing surfaces of ordinary living rooms to 80 deg F uniformly is out of the question. Since normal infiltration changes the air in a house from 1 to 3 times per hour, it was decided to limit these studies to such an air flow with but portions of the enclosing surfaces heated.

Altogether 104 units were used in the walls and ceiling connected 2 in series across the power supply lines through an "on" and "off" switch for each pair. Power was controlled with a voltage regulator. Thus the position and extent of the heated wall or ceiling area, as well as its temperature, could be varied at will. A master switch in series with an adjustable thermostat and wall meter mounted inside the room completed the electrical equipment.

A single observation required about 60 individual readings for a complete picture of the effect of any set of conditions. The aim, of course, was to examine a sufficient number of conditions to predict comfort and power requirements for any conditions where low temperature radiant heat is to be used. In Table I the data of 10 typical observations are summarized.

### DISCUSSION OF RESULTS

For purposes of estimating power requirements in any applications using this type of heat and also for the purpose of having a check on air flow and power input, it was thought desirable to account for all the power used. Items 18 and 19 of Table I show how closely this was done. The thermal conductivity of the walls was tested accurately so that the dissipation through the walls could be determined fairly accurately with a sufficient number of inside and outside temperatures. Failure to obtain enough outside temperatures for observations 1 and 4 resulted in the loss of this estimation. Another source of inaccuracy in this regard was the inability to obtain an accurate average entrance air temperature. Some of the heat within the test room passing through the ceiling served to supply part of the preliminary temperature rise of duct air while the rest was drawn from the space and building around the room.

It is a difficult matter to predict accurately the effects of temperature, position, and orientation of the heated panels on an occupant of the room, even though he might stand erect in the center of the room. The radiant flux to a person in the panel heated room is, of course, a function of: the solid angle, temperature, and orientation of the heat source; and the outside area, temperature, and position of the recipient. It would not be a simple matter to compute accurately the integrated solid angle of all room surfaces integrated in turn over the person of the occupant with due regard for orientation of both person and walls. A rough measure of comfort, however, has been computed; this has been added as item 26 at the bottom of Table I under the caption "comfort index."

To obtain a value of the comfort index for each set of conditions a cylinder was postulated in the center of the room having radiating and convecting surfaces approximating those of the average man with the same general shape and size as regards volume. It was assumed for instance that there were 20 sq ft of convecting surface and 16 sq ft of radiating surface with an emissivity of 0.9 for the temperatures under consideration.

The equation for convection from such a vertical cylinder was taken as $H = 0.35\ \theta^{1.25}$ where $H$ is expressed in Btu per hour per square foot of surface and $\theta$ is surface temperature rise in degrees F. Figure 4 shows the loss based on this equation in Btu per hour from a vertical cylinder with a uniform surface temperature of 80 deg F to air at temperatures under 80 deg F. Figure 3 shows the radiant interchange of heat between the assumed cylinder and its solid surroundings in Btu per hour.

After these curves were drawn they were checked by applying standard conditions, that is, the body heat loss with air at 70 deg F and walls at 68 deg F was found by the use of these curves to be 300 Btu per hour, which is approximately correct according to the previously cited work done at the American Society of Heating & Ventilating Engineers research laboratory. The negative sign before the comfort index (item 26) in Table I indicates a loss by radiation and convection from the cylinder of the specified number of Btu per hour for each case. Thus −300 Btu per hour would indicate comfort while −447 would indicate a chilly condition and −64 a much too warm condition. No great accuracy is claimed for this system, but it is presented as the best available at this time. It must be borne in mind that if this cylinder should wander over toward one of the heated wall panels, thus subtending a greater solid angle of warmth, these comfort indices would not apply as accurately as if it stayed in the center of the room.

The curves developed, as a result of the work described here, were tested by applying some recent results obtained at the research laboratory of the A.S.H.V.E.[3] Three walls of a 5x6x6-ft room there were cooled while the air temperature was raised until comfort was obtained. One point of the A.S.H.V.E. comfort curve gave the temperature of 3 walls at 45 deg F with air at 78.9 deg F. The comfort index computed by the method here developed for such a condition is −284. If the floor, ceiling, and fourth side wall had been assumed at a temperature slightly lower than that of the air, the index would have approached very nearly the ideal of −300. Since the room was so small it was more easily possible to take into account the solid angle

TABLE 1—SUMMARY OF DATA FOR 10 TYPICAL OBSERVATIONS

| 1. Observation No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2. Outside air temp. (° F) | 32.2 | 33 | 16.7 | 29.7 | 46.5 | 37.6 | 44.3 | 43.7 | 36.7 | 20.4 |
| 3. Air changes per hour | 1.15 | 1.18 | 3.1 | 3.3 | 6.1 | 3.2 | 3.3 | 3.2 | 2.1 | 2.1 |
| 4. Temp. of entrance air (° F) | 55.0 | 56.0 | 33.5 | 49.4 | 53.3 | 48.3 | 55.4 | 55.9 | 54.1 | 43.3 |
| 5. Temp. of exit air (° F) | 66.3 | 64.0 | 59.3 | 68.6 | 66.0 | 68.2 | 71.4 | 74.1 | 69.1 | 67.8 |
| 6. Temp. rise of air in room (° F) | 11.3 | 8.0 | 25.8 | 19.2 | 12.7 | 19.9 | 16.0 | 18.6 | 15.0 | 24.5 |
| 7. Temp. of air surrounding room (° F) | ... | 58.0 | 44.0 | ... | 61.4 | 60.0 | 65.6 | 65.8 | 63.1 | 57.6 |
| 8. Area of heated ceiling (sq ft) | 192 | 192 | 144.0 | 144.0 | 96.0 | 96.0 | 96.0 | 96.0 | 96.0 | 96.0 |
| 9. Temp. of heated ceiling (° F) | 82.3 | 78.4 | 87.5 | 105.1 | 96.0 | 95.3 | 91.2 | 104.4 | 89.1 | 107.1 |
| 10. Area of cold ceiling (sq ft) | ... | ... | 48.0 | 48.0 | 96.0 | 96.0 | 96.0 | 96.0 | 96.0 | 96.0 |
| 11. Temp. of cold ceiling (° F) | ... | ... | 60.0 | 69.5 | 66.8 | 66.9 | 70.9 | 73.0 | 67.9 | 66.3 |
| 12. Area of heated walls (sq ft) | 36 | 36 | 36.0 | 36.0 | 84.0 | 102.0 | 84.0 | 84.0 | 84.0 | 84.0 |
| 13. Temp. of heated walls (° F) | 81.2 | 77.2 | 90.0 | 111.6 | 95.0 | 97.0 | 90.8 | 103.9 | 103.9 | 101.2 |
| 14. Area of cold walls (sq ft) | 458 | 458 | 458 | 458 | 410 | 392 | 410 | 410 | 410 | 410 |
| 15. Temp. of cold walls (° F) | 62.7 | 66.0 | 60.0 | 68.5 | 67.0 | 66.3 | 70.4 | 73.7 | 68.8 | 67.2 |
| 16. Watts lost through walls | ... | 1,076.0 | 1,876 | ... | 919 | 1,440 | 1,057 | 1,457 | 1,007 | 1,932 |
| 17. Watts lost to air | 114 | 83.0 | 700 | 575 | 690 | 570 | 475 | 527 | 280 | 462 |
| 18. Total dissipation (computed) | ... | 1,159 | 2,576 | ... | 1,609 | 2,010 | 1,532 | 1,984 | 1,287 | 2,394 |
| 19. Watts input meter reading | 1,200 | 1,200 | 2,100 | 2,500 | 1,800 | 2,400 | 1,450 | 2,200 | 1,400 | 2,900 |
| 20. Watt density (watts per sq ft) | 5.3 | 5.3 | 11.6 | 14.0 | 10.0 | 12.1 | 8.0 | 12.2 | 7.8 | 16.1 |
| 21. Avg enclosure temp | 68.9 | 65.0 | 66.1 | 76.7 | 73.0 | 74.0 | 75.1 | 80.2 | 73.2 | 75.4 |
| 22. Avg air temp., thermocouple | 66.0 | 63.0 | 59.2 | 68.4 | 66.0 | 68.3 | 70.4 | 73.7 | 68.8 | 67.5 |
| 23. Avg air temp., mercury thermometers | ... | 64.0 | ... | 70.0 | 68.0 | 70.0 | 72.7 | 76.0 | 70.7 | 70.3 |
| 24. Per cent of ceiling area heated | 100 | 100 | 75 | 75 | 50 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Per cent of side wall area heated | 7.3 | 7.3 | 7.3 | 7.3 | 17.0 | 21.0 | 17.0 | 17.0 | 17.0 | 17.0 |
| 25. Per cent of enclosure surface heated | 26.0 | 26.0 | 20.5 | 20.5 | 20.5 | 22.6 | 20.5 | 20.5 | 20.5 | 20.5 |
| 26. Comfort index | −353 | −447 | −516 | −189 | −285 | −232 | −187 | −64 | −240 | −226 |

Dimensions of room, 12x16x8.8 ft. Inside areas in sq ft: ceiling, 192; floor, 192; side walls, 494; total, 878. Space, 1,690 cu ft.

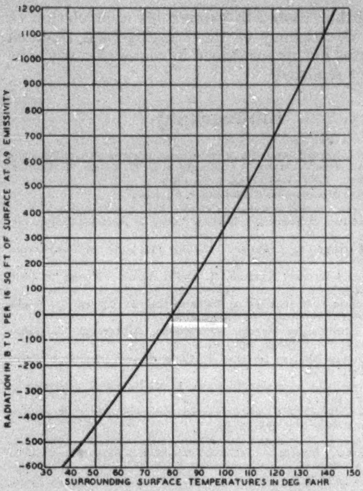
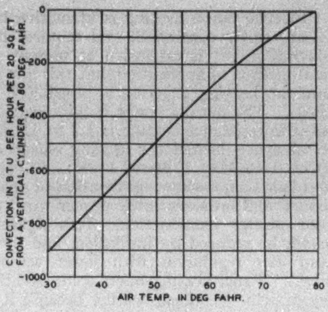


Fig. 3—(Left) Radiation From a Vertical Cylinder Having the Approximate Size and Shape of an Average Man, With the Outside Temperature Maintained at 80 Deg F

Fig. 4—(Right) Convection From a Vertical Cylinder Having the Approximate Size and Shape of an Average Man



and orientation of surfaces, which also raised the computed radiation losses. It is believed, therefore, that the method developed for predicting comfort conditions in radiant heated spaces is satisfactory for all practical purposes.

The method of using these curves is simple enough as is illustrated in the following example:

Let area of total enclosure surfaces be 878 sq ft. Assume:
96 sq ft of ceiling at 107° F
96 sq ft of ceiling at 66° F
84 sq ft of walls at 101° F
410 sq ft of walls at 67° F
192 sq ft of floor at 69° F
Air temperature...... 67.5° F

From the radiation and convection curves we have:

*Radiation*

96 sq ft at 107° = +460 × 96 = +44,100
96 sq ft at 66° = −202 × 96 = −21,000
84 sq ft at 101° = +351 × 84 = +29,500
410 sq ft at 67° = −195 × 410 = −80,000
192 sq ft at 69° = −165 × 192 = −31,500
878 = −58,900

and the average is $\frac{-58{,}900}{878} = -67$

*Convection* for air at 67.5 = −160
Total dissipation = −227.

Data for these figures were taken from observation No. 10.

One of the outstanding features of this heating method as observed in the experimental work described here is the remarkable uniformity of air temperature throughout the entire room. The fine-wire thermocouple used to explore various parts of the room indicated air temperatures not differing more than a degree from each other. As an example, details of observation No. 6 show temperatures in degrees F as follows:

| | |
|---|---|
| 6 in. below ceiling center of room | 69.1 |
| Breathing line | 68.8 |
| 6 in. above floor | 68.2 |
| Front left corner 14 in. above floor | 68.2 |
| At breathing line for one seated back of desk | 69.2 |
| Right side near bookcase thermometer | 68.1 |

The floor was covered with a chenille carpet the temperature of which, after equilibrium conditions were established, was from 2 to 3 degrees higher than that of the air.

From an examination of Table I it is apparent that conditions represented by observations 1 and 5 come nearer to fulfilling comfort requirements than any of the others, their comfort indices being respectively, −353 and −285; however, No. 1 is too cool, and No. 5 is too warm. For No. 5 the air temperature is 7 deg F lower than the average enclosure temperature. It may be pointed out also that by raising the average enclosure temperature some 5 deg above that usually prevailing for ordinary heating methods, the air temperature is lowered 4 deg in this particular instance and should have been lowered another degree for ideal conditions.

In general, no effort was made to find the optimum conditions for the greatest number of people, but comfort always was aimed at and with 2 exceptions (observations 3 and 8) the room was not extremely uncomfortable for any of the conditions recorded in the Table I.

The method of using rather extensive areas at moderately low temperatures has been given more study in Great Britain than in this country. Several references relative to this so-called panel heating are included in the bibliography (references 4 to 15, inclusive).

Humidity was neglected in this work because its effect on human comfort at a dry bulb temperature of less than 70 deg F is not so important as it is at higher temperatures. (See American Society of Heating & Ventilating *Guide* for 1931, p. 409, for curve of heat and moisture losses as functions of the dry bulb temperature.) In fact one of the advantages of cool air and warm walls is that not only is the relative humidity naturally higher, but its effect as a comfort factor is much less important than it is for warmer air.

Electric house heating is attractive because it is clean, easily controlled, and requires no labor for operation. It is expensive at present power rates and method of application, but this low temperature radiant heating suggests a possibility of lowering costs. The normal power requirements for straight electric resistance heating is 1.2 to 1.5 kwhr per cu ft of space heated per heating season of 212 days (Oct. 1 to May 1) based upon: 40 deg F average outdoor temperature; infiltration of one change per hour; and ordinary brick veneer wood frame, lath, and plaster construction. This figure no doubt could be reduced by insulation, and by close night and day regulation with lower temperatures at night. Panel heating offers some additional saving in straight resistance heating because it is unnecessary to warm the air quite as much where radiation plays a greater part. But this low temperature wall heat will make a tremendous difference if reversed refrigeration becomes generally used. By pumping heat from the outside to a moderate temperature of say 80 deg F, the coefficient of performance of the heat pump is much higher than if this heat were to be pumped in at a temperature of 180 deg F. In fact with one-cent power and reversed refrigeration operating between 40 and 80 deg F, the actual operating costs become competitive with coal.

Even with present power rates electric wall heating should be applicable to warmer climates where the necessity for heat occurs only an hour or so in the mornings and evenings during the winter season. The type of wall units described here can be made quite inexpensive so that the cost of equipping an entire house would be but little more than the cost of ordinary lath and plaster.

### SUMMARY AND CONCLUSIONS

Briefly summarized, the important findings of this investigation and conclusions reached are as follows:

1. The results of observations on space heating with rather extensive surfaces at moderately low temperatures have been worked into a practical method of predicting comfort with various combinations of wall and air temperatures.

2. The air temperature may average from 2 to 8 deg lower than the average enclosure temperature, which results in a saving of heat.

3. Most of the radiating surfaces were put in the ceiling; this seems to be desirable to cut down heat losses, and is not objectionable from the standpoint of comfort. It no doubt would be desirable to put warm panels in selected places in the side walls, as, for instance, under windows to prevent downward air currents and nullify to some extent the body's radiation to the cold window surfaces.

4. A remarkably uniform temperature was found to prevail within the room as a result of the heating method here presented.

5. The low temperature radiant heating method in combination with reversed refrigeration would lower the operating costs of electric heating to a point where it might be competitive with heating by gas and oils or even coal.

6. Power consumption varied from 5.3 to 16.1 watts per sq ft. It is possible that a 2-range provision might be made with a density of 50 watts per sq ft for accelerated effects on a cold morning for a few minutes after the power is turned on, and $^1/_4$ of that density for steady application. Where 1 sq ft of heated area is used for each 10 cu ft of space heated, $12^1/_2$ watts per sq ft should be ample for quite severe weather. Modifications in outdoor temperature could be taken care of with a thermostat set to throw the power on or off according to requirements.

The author wishes to express his appreciation to Mr. W. C. Stickney of the Westinghouse research laboratories for his assistance in connection with the work here reported.

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## Discussion

**R. E. Hellmund:** In view of the fact that an appreciable percentage of air-conditioning and comfort-creating equipment will be operated by electrical means, a great many electrical engineers will be brought into contact with this work. This applies to design, application, and utility operating engineers. Unquestionably these engineers will find it easiest to understand the fundamentals entering into human comfort by considering the analogy between the human machine and the electrical machine as well as certain differences that exist between the two.

Electrical apparatus, under given loads, usually has certain losses which appear as heat and which have to be dissipated through radiation and convection. In order to make dissipation of this heat possible by these two phenomena, the electrical machine temperature adjusts itself to certain differences between the temperature of its surface and that of the surrounding air and objects. The human machine, like the electrical machine, also has certain losses appearing as heat which have to be dissipated. These losses, as in the electrical machine, depend to some extent upon the load to be carried; in sedentary occupations they are in the neighborhood of 117 watts. The human mechanism apparently regulates these losses in such a way that they are fairly constant over a certain range of surrounding conditions. In addition, the body seems to be able to vary these losses under surrounding conditions of either extreme, but when this is necessary it is usually outside of the range of comfort and therefore this factor can be neglected whenever artificial means are applied to create comfort. Therefore, the principal difference to be considered between the electrical and the human machine is that the human organism under normal conditions maintains a more or less constant temperature regardless of surroundings. The necessary equilibrium nevertheless can be maintained because the human body loses heat not only by radiation and convection but also by evaporation (both through the breathing organism and through perspiration of the outer skin); the nearest analogy to this in the electrical field is a liquid rheostat operated at the boiling point of the liquid.

This point is illustrated further in Fig. 1. In Fig. 1*A*, assuming normal conditions in a heated room during a cold day, it is assumed further that there is a definite difference in the temperature of the clothing worn and that of the surrounding walls. Under these assumptions, the loss by radiation (represented by line I) is of course constant regardless of the air temperature. The loss by convection is zero with the air temperature equal to that of the clothing and it increases with the increasing difference between the air and the clothing temperature. In other words, the loss by radiation and convection can be illustrated by curve II. It follows then that the difference between this curve and curve III, representing the total loss, must be dissipated through evaporation, and under the assumed conditions the greatest comfort is obtained with a loss through evaporation as indicated by the line *CD*, at a temperature of about 75 degrees and with a relative air humidity of about 50 per cent.

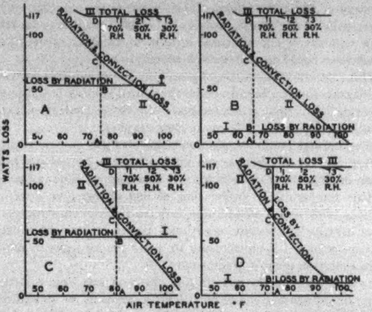

FIG. 1.

In Fig. 1*B*, it has been assumed that the difference between the temperature of the wall and that of the clothing is appreciably smaller than in the previous case, a condition that may be obtained during a somewhat warmer day in winter or by means of artificially heating the walls during colder days. It is at once evident that with the same humidity and the same amount of loss through evaporation (*CD*), comfort will be possible with a much lower air temperature, probably in the neighborhood of 66 degrees. The loss by convection may be increased by increased air velocity across the person, such as might be caused by a draft in winter time, a condition that is illustrated in Fig. 1*C*. With a loss by radiation the same as in Fig. 1*A*, the convection curve is much steeper than in that figure. Naturally, the loss by evaporation also increases with the air velocity and therefore *CD* is assumed somewhat larger. Fig. 1*C* shows that on a cold winter day, with cold outside walls and certain drafts, an air temperature of above 80 degrees will be required to obtain the same comfort as with the previous figures. On the other hand, Fig. 1*D* assumes the same radiation loss as *B* but increased air velocity, and indicates comfort with a temperature around 75 degrees. As already indicated, the relative humidity has been assumed constant around the average value. However, even if the humidity should be lower, as is frequently the case in winter, this simply means that the loss by evaporation will slightly increase, which for equal comfort means that the loss by convection should decrease. This makes it necessary to maintain a somewhat higher air temperature, which as a rule can be done very readily.

In summer time, the various factors previously mentioned are of equal importance, except that comfort is influenced largely by the fact that humidity tends to be high rather than low as in winter. For the purpose of indicating the points at which marked discomfort begins, arrows 1, 2, and 3, relating to different values of relative humidity, have been added to the figures. Fig. 1*A* may now represent a summer day after a cold spell, leaving the walls in cool condition and permitting some radiation. As a matter of course, a temperature of 75 degrees again means comfort. However, if it is assumed that during such a day the air temperature rises to about 80 degrees and that the humidity is 70 per cent, discomfort would start due to perspiration. Fig. 1*B* corresponds to a condition often met with upon entering a room after a relatively hot day. The walls are hot, permitting very little radiation from the person, and considerable discomfort will be felt with a humidity of about 70 per cent even though the evening air admitted through the windows may have cooled down to about 70 degrees.

Up to the present time, the most common means used for obtaining relief in summer has been the electric fan, which increases the loss of heat by convection as indicated in *C* and *D*. Fig. 1*C* shows that with cool walls and with 70 per cent humidity, fair comfort might be obtained with an air temperature up to about 86 degrees under the assumptions made; while with hot walls, as they are most likely to be, discomfort will start around 76 degrees with the curve shown in *D*. Although it is frequently stated that fans, because they do not actually cool the air, are not useful, it is evident that they are quite effective in dissipating heat and creating comfort. The principal shortcoming of the electric fan lies in the fact that the air currents are uni-directional and do not uniformly cool the body surfaces. Furthermore, it is difficult to regulate for the most advantageous air velocity. It should be pointed out also that the steepness of the convection curve as obtained with fans means that a relatively small decrease in air temperature may lead to discomfort under certain conditions. Nevertheless, the fan, on account of its convenience and low cost, will continue to be a most popular means of obtaining some degree of comfort in the hot weather.

On the other hand, the more modern air-conditioning equipment, bringing about de-humidification, lowering the air temperature, and possibly artificial cooling of the walls, can be much better regulated and therefore is the only way in which comfort can be realized safely under all summer conditions. However, even here it is important that the effect of the various factors be fully appreciated and taken into account if misapplications are to be avoided. It is hoped that the simple curves given with this discussion may assist along this line, although, for the sake of simplicity, some assumptions not strictly correct were made and some factors have been neglected. A more detailed study of the conditions indicates, for instance, that the change in temperature drop through the clothing and skin, which has been neglected in the curves, is an important factor in broadening the zone of relative comfort. The simplified method of attack was chosen merely because it may be more suitable for conveying the fundamental ideas to the average engineer than the various rather complicated charts in use by air-conditioning specialists.

**B. R. Teare, Jr., and Louis Levine:** This discussion is concerned mainly with 2 items treated in the paper:

1. The "comfort criterion" proposed by the author.
2. The possible power savings obtainable through panel heating.

On the basis of material presented by Mr. L. W. Schad, research performed at the A.S.H.V.E. Research Laboratory (reference 3 of the paper), and calculations made by the writers, the value of the proposed comfort criterion seems doubtful.

The results obtained from a problem assigned several months ago to the Thermal Engineering Section of the Advanced Course in Engineering of the General Electric Company are given in the following. The class was asked to find various combinations of room air and wall temperatures such that the same overall conditions of comfort obtained as with walls and air at 70 deg F (middle of the winter comfort zone). The method used in solving this problem fundamentally was the same as that used by Mr. Schad in his calculations, but the results were expressed in different form. The advantage of this procedure is that it permits checking the calculations against the A.S.H.V.E. test data, and permits one to see at a glance the wall temperature required for any air temperature it is desired to maintain.

The main assumptions used in solving this problem were as follows:

1. Heat dissipated by an occupant remains constant at 400 Btu per hour. This is divided between evaporation, constant at 95 Btu per hour, and radiation and convection, the sum of which was constant at 305 Btu per hour. This data was taken from the A.S.H.V.E. Guide.

2. A human occupant may be represented, for purposes of calculation, by a cylindrical body having a surface area of 19.5 sq ft. The total area is taken to be effective in convection; 85 per cent of this in radiation.

3. Emissivity of the body surface is taken as 0.93.

4. The heat loss by convection is

$$h_c = 0.22\,(T_o - T_A)^{1/3} \text{ Btu per sq ft per hr}$$

The heat loss by radiation is

$$h_r = 0.93 \times 1.07\,(T_o - T_W)$$

where $T_o$ = body temperature
$T_A$ = air temperature
$T_W$ = wall temperature

The radiation expression is a linear approximation to the fourth power law, sufficiently accurate for the small temperature range used. This and the convection expression were taken from "The Basic Laws and Data of Heat Transmission" by W. J. King, *Mechanical Engineering*, March-August, 1932.

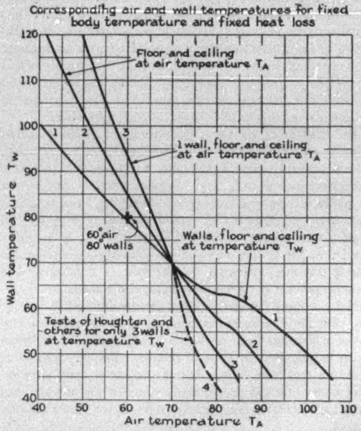

FIG. 2.

5. A condition of unchanged comfort is obtained by maintaining an unchanged body surface temperature and an unchanged body heat loss.

Three different cases were considered in this problem:

1. Walls, ceiling, and floor all at the same temperature, $T_W$.

2. Walls all at same temperature, $T_W$; ceiling and floor at air temperature, $T_A$.

3. Three walls at temperature $T_W$; one wall, ceiling, and floor at air temperature, $T_A$. This case corresponds to conditions established in the work done at the A.S.H.V.E. Research Laboratory by F. C. Houghton and others.

In case 2, it was assumed further that 75 per cent of the body radiating area radiates to the wall temperature, $T_W$, and 25 per cent radiates to the ceiling and floor at air temperature, $T_A$. In case 3, these figures were taken as 56 per cent and 44 per cent, respectively (56 per cent = $^3/_4 \times 75$ per cent).

The results of this analysis are given in Fig. 2. In addition, test data gathered at the A.S.H.V.E. Laboratory on the effect of cold walls are shown as a dashed curve. The curves seem to indicate that the combination of air at 60 deg and enclosing surfaces uniformly at 80 deg represents a comfortable condition, as claimed by Mr. Schad. On the other hand, if the method of calculation were accurate, curve 3 should coincide with the experimental curve 4, which represents a careful piece of research. Actually, there is considerable divergence between these two curves, and this tends to cast doubt on the accuracy of the calculations. This discrepancy, together with the others pointed out above, leads us to believe that it may be safer to place reliance in experimental criteria of comfort rather than in calculations based on questionable assumptions.

With regard to the matter of power consumption, it is hard to see justification for Mr. Schad's claim that panel heating promises lower operating costs than other methods of electric heating, which are notoriously expensive. To quote from his paper:

"The normal power requirements for straight electric resistance heating are 1.2 to 1.5 kwhr per cu ft of space heated per heating season of 212 days (Oct. 1 to May 1) based upon: 40 deg F average outdoor temperature; infiltration of one change per hour; and ordinary brick veneer wood frame, lath, and plaster construction.... Panel heating offers some additional saving in straight resistance heating because it is unnecessary to warm the air quite as much as where radiation plays a greater part."

It would seem to the writers that the heat loss from a structure using radiant heating would be at least as great as for an equivalent structure using an efficient method of convection heating, and really this is the criterion that determines operating costs. It is true that with lower air temperature the infiltration loss and the conduction loss through unheated portions of external walls is somewhat reduced. But it is equally true that where radiant panels are installed in external walls, as they should be to counteract radiation from the body to those cold surfaces, the conduction loss through those wall sections tends to increase. This can be seen from the following:

Heat loss = constant × (temperature of inside wall surface − outside air temperature)
= constant × $\Delta T$

Without panel heating, inside wall temperature = 65°
Average outside temperature = 40°
$\Delta T = 25°$
With panel heating, inside wall temperature = 80° to 110°
Average outside temperature = 40°
$\Delta T = 40°$ to 70°

This loss may be reduced by using additional insulation, but, of course, such insulation would aid *any* heating system.

Further evidence leading to the same conclusion may be derived from 2 reports of experimental work published in recent years. The first is by L. J. Fowler and is given as reference 4 in Mr. Schad's paper. A 21,250-cu ft home was heated by electric panels of 20 kw capacity from October 1, 1928 to May 1, 1929, holding the interior temperature at 60 deg F while the outdoor temperature averaged 43 deg F. This corresponds to a heating season of 3,600 degree days. The actual energy consumed was 30,300 kwhr or 1.42 kwhr per cu ft of space heated. This falls in the range given by the author for resistance heaters, and for conditions that are more favorable than he assumed.

The second report is by E. B. Dawson and J. F. Lamb, of the Westinghouse Company, "Electrically Heated Houses" published in the *Electrical World*, January 12, 1929. A 14,000-cu ft home, well insulated with corkboard, weatherstripped, and calked, and heated by a thermal storage system with electric heat required 20,650 kwhr for a heating season of 6,186 days. If this figure be corrected to a heating season of 4,600 degree days, which would correspond to an average outdoor temperature of 43 deg and the usual interior base temperature of 65 deg, it shows the power consumption would have been 1 kwhr per cu ft of space heated, and that without panel heating. Of course, this figure is not directly comparable with the preceding one because it does not apply to the same structure, but it indicates results that can be obtained.

As regards the use of a heat pump, this would no doubt reduce operating costs materially. The major part of such reduction must, however, be credited to the heat pump itself, and not to the panel heating auxiliary. Low temperatures of heating air can be obtained without panel heating simply by using a large condenser surface, which also would be necessary if panel auxiliaries were employed. If lower air temperatures are to be used in the latter case, a correspondingly larger condenser must be used for the same amount of heat delivery; however, a slightly better coefficient of performance perhaps can be obtained.

It is not the intention of the writers to depreciate the work being done by Mr. Schad. The field under discussion is a new one and there is much to be learned. Further research may indicate the desirability of modifying our heating methods for reasons of comfort, health, cleanliness, and ease of control. Power rates may be reduced to the point where we may be willing to pay a slight differential for the undoubted advantages of electrical heat in one form or another. Consequently, such work as the present is exceedingly valuable and deserves all possible encouragement.

**L. W. Schad:** The author is indebted to Mr. R. E. Hellmund for his discussion presenting a more general picture of comfort requirements. It is true that all the factors must be evaluated so that the essential ones may be taken into account for the most satisfactory design and application of year round comfort producing equipment.

Messrs. B. R. Teare, Jr., and Louis Levine by questioning the comfort criterion as proposed by the author, emphasize the need for a simple and accurate method of estimating radiation effects on human comfort under all conditions. The exact mathematical solution as suggested by the author is by no means simple and would be more or less inadequate where the warmed panels were not distributed symmetrically, for one solution would hold for only one position of occupancy.

The method suggested by Messrs. Teare and Levine perhaps is no more satisfactory than the approximate method proposed in the paper, since it also must be dependent upon distribution of panels, room size, and position of the occupant. However, both methods are aims in the desired direction and if substantiated perhaps with refinement by further experiments, should be very useful in designing panel heating systems.

*Fuel Saving by Panel Heat:* If it is found satisfactory to place most of the warmed panels in ceilings or inside walls instead of mainly in the outside walls, the objection raised by Messrs. Teare and Levine that the heat loss will be as great with panel heating systems as with good convection systems because of the increased gradient from inside wall surface to the outdoor air is invalid. However, it is doubtful whether any great saving can be effected by the panel system here in America without the use of the heat pump. Claims are made by our British friends that there is a substantial saving effected by the use of panel heating systems but British comfort standards are somewhat different from ours. The writer does not believe, however, that to increase the condenser size in the case of the heat pump would be as desirable or effective in raising the overall efficiency as would panel heating in conjunction with the heat pump. The usual warm air system delivers air at 140 degrees F or over according to the severity of the weather. The condenser of the heat pump would have to operate at a top temperature of 80 degrees F. Hence the register air temperature would be less than 80 degrees and still must deliver the required amount of heat. The result would be a circulation of much greater air volumes and, of course, serious drafts unless elaborate precautions were taken to prevent them.

# Improvements in Mercury Arc Rectifiers

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***Synopsis.**—An improved design of section for the sectional mercury arc rectifier is described, together with the manner of assembling into the sectional unit. The paper includes also a brief description of the auxiliaries used. The units being supplied to the Board of Transportation, for the Fulton Street section of the independent subway system in New York City, are described specifically. Performance characteristics, which include arc voltage curves, determined from both laboratory tests and operating service are given. Factors determining design features are discussed.*

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THE PRINCIPLE of building large capacity rectifiers in sectional form was discussed in A. L. Atherton's paper ("High Capacity Rectifier Efficiency Improved by Sectionalizing," A.I.E.E. Trans., v. 51, 1932, p. 511–15) presented at the 1932 A.I.E.E. winter convention. Obviously, the successful achievement of a sectional rectifier, without its becoming prohibitively large, involved the development of a rectifier section greatly reduced in size from the familiar conventional rectifier of 500 to 1,000 kw capacity. Because of the characteristics of the device, this reduction in size of section inevitably resulted in a corresponding reduction in arc drop with a further enhancing of the advantage of the sectional arrangement. The design was based upon a 1,250-amp section, which is approximately the rating above which difficulties due to size begin. Mr. Atherton's paper briefly describes the first design of sectional rectifier. Since that time, considerable improvement has been made both in performance and convenience of operation. This paper describes the 3,000-kw 625-volt unit being installed on the Fulton Street line of the Independent Subway System of the City of New York; this unit is typical for any capacity above 750 kw at 600 volts. The paper also briefly describes smaller rectifiers for capacities below 750 kw.

During recent years great advances have been made in the knowledge of the fundamentals of the electric arc. This information facilitated the improvements made in the sectional mercury arc rectifier. (See "Backfire in Mercury Arc Rectifiers," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 51, 1932, p. 92–104; "Mercury Arc Rectifier Research," by A. W. Hull and H. D. Brown, A.I.E.E. Trans., v. 50, 1931, p. 744–56; and "A New Method for Initiating the Cathode of an Arc," by J. Slepian and L. R. Ludwig, A.I.E.E., Trans., v. 52, 1933.) There are certain advantages in the arrangement of parts in the conventional type of metal tank rectifier. In the past, as the result of available experience, it was believed that a rather definite relationship existed between the cooling surface area and volume of a rectifier, and the maximum current carrying capacity. The empirical relationship adopted required a tank so large that its size was objectionable. It was pointed out by Dr. J. Slepian of the Westinghouse Company, East Pittsburgh, Pa., that no fundamental relationship of this sort exists. Doctor Slepian further suggested that since all vapor that comes into contact with a cooled surface condenses (thus the temperature of this surface determines the pressure of the vapor in the regions adjoining) in order to maintain the desired vapor density in the arc conducting regions it is necessary only to clear the way for the vapor to reach the condensing surfaces. If these surfaces be maintained at the desired temperature there is no limitation, that is approached in mercury arc rectifier practice, to the watts per unit area that can be dissipated. Therefore, in designing the improved sectional rectifier the basis used was a conventional rectifier with which a great deal of successful experience was available; but no attention was given to area of cooling surfaces, and the only considerations were that ample passages be provided for the smooth flow of vapor from the source at the cathode to the condensing surfaces, so as to prevent undesirable rises in pressures. Also, the parts were so arranged that the vapor flow would sweep to the vacuum pumping connection such permanent gases as gather, and prevent any accumulation that would keep the vapor from reaching the cooling surfaces or from entering the arc path with objectionable results. Thus, since the amount of vapor coming from the cathode is proportional to the current and since it is essential that the correct vapor density be maintained, the current carrying limit is determined by the provisions for disposition of the mercury vapor, in addition, of course, to the thermal limitations of the current conducting parts. The voltage limitation of a rectifier is one of arc back which determines the amount of deionizing required in the arc path. The influence of this on size is small compared to that of provisions determined by current.

It is questionable if at the present time a temperature can be specified at which rectifiers in general operate with lowest arc drop (See "Recent Developments in High Current Mercury Arc Rectifiers," by E. H. Reid and C. C. Herskind, A.I.E.E. Trans., v. 52, 1933). Of prime importance is the ability to rectify without arcing back. Up to a certain point, raising the temperature lowers the arc drop; but also, except for low temperatures at which surges occur, it lowers the ability to withstand arc back. To counteract the tendency to arc back, in the present forms of rectifiers deionizing surfaces are interposed in the arc path; these raise the arc drop. Therefore, both temperature and deionizing devices must be considered and the optimum balance chosen. For a given arrangement of parts, the higher the temperature the greater will be the stability of the arc and the freedom from voltage surges. Of course

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* Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the summer convention of the A.I.E.E., Chicago, Ill., June 26–30, 1933.*

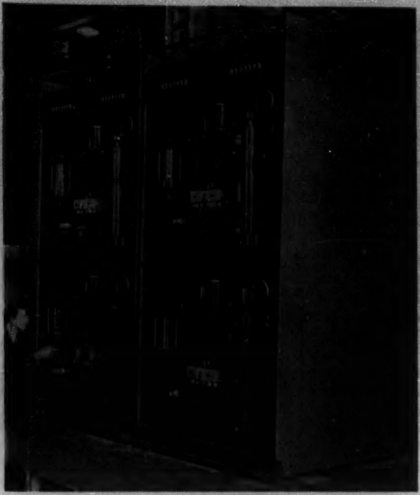


Fig. 1—3,000-Kw 625-Volt 4-Section Mercury Arc Rectifier With Truck Type Sections Which Can Be Taken Out of Service in a Few Seconds

Fig. 2—One Section of the Rectifier Shown in Fig. 1

These can be arranged in multiple for any capacity desired with no loss of efficiency, and the requirement for spare capacity reduced with increased size. Section shown is assembled with complete independent set of auxiliaries and contacts for truck type mounting

a high water discharge temperature conserves the cooling water required, but usually the importance of this is secondary to that of rectifier efficiency.

Figure 3 shows a cross section of the resulting design, and indicates not only the compact arrangement of parts but also the wide, smooth paths for the vapor flow as discussed. The rectifier tank is equipped with a small dome from which the permanent gases are exhausted. Such gases as accumulate gather in this dome and, therefore, do not go into the region around the anode upon fluctuations in load with consequent fluctuations in vapor flow.

In addition to the large size of former rectifiers due to condensing surface constants, the usual form of anode shield and the provision for cooling the anode terminal with water, which frequently is employed, imposed a height requirement that was prohibitive. To reduce the anode structure length, additional grid length was substituted for the usual extra shield length with a net saving of several inches. Because of the narrower passages of the grid, each unit of grid length is equivalent to a much greater length of shield. The substitution of a small solid anode radiator for the necessarily large water filled radiator is the relatively simple matter of designing the parts so that the desired temperature gradient is obtained with a solid anode stem. This, of course, requires an arrangement of parts such that no part of the effective insulation operates at a temperature at which the insulating value of the material is reduced.

The anode of the sectional rectifier is shown in Fig. 4. Graphite is used as the anode head because it is not seriously damaged by arc back. Quartz is used for the grid because it is an insulating material with a high melting point and satisfactory mechanical strength. Making the grid of insulating material prevents the formation of a cathode spot on the grid with the resulting damage when passing heavy currents. Quartz is used also as anode insulation in critical locations, because it maintains its insulating qualities at relatively high temperatures and the tendency for breakdown to occur at the junction between quartz and a conductor is less than with most insulating materials. Shields and baffles are so arranged as to keep the spaces adjacent to the insulation deionized, thus keeping the insulation clean by preventing sputtering, and reducing the

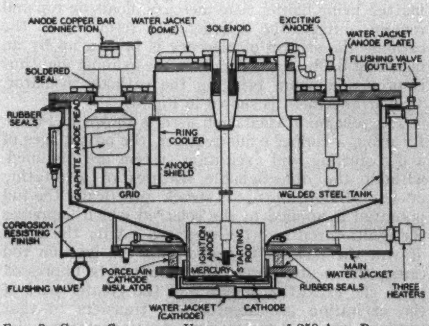

ANODE COPPER BAR CONNECTION
WATER JACKET (DOME)
SOLENOID
EXCITING ANODE
WATER JACKET (ANODE PLATE)
FLUSHING VALVE (OUTLET)
SOLDERED SEAL
RUBBER SEALS
GRAPHITE ANODE HEAD
RING COOLER
ANODE SHIELD
GRID
WELDED STEEL TANK
CORROSION RESISTING FINISH
IGNITION ANODE
STARTING ROD
MERCURY
PORCELAIN CATHODE INSULATOR
FLUSHING VALVE
MAIN WATER JACKET
RUBBER SEALS
THREE HEATERS
WATER JACKET (CATHODE)
CATHODE

Fig. 3—Cross Sectional View of the 1,250-Amp Rectifier Section Shown in Fig. 2

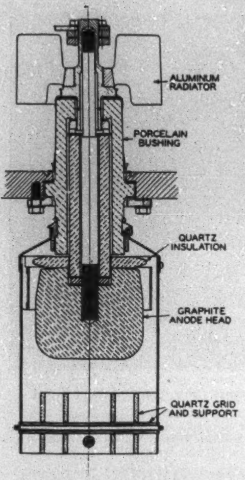


FIG. 4—CROSS SECTIONAL VIEW OF RECTIFIER ANODE

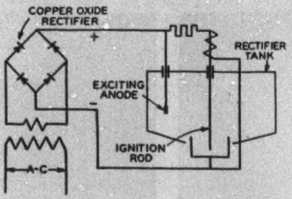


FIG. 5—SCHEMATIC DIAGRAM OF IGNITION AND EXCITATION SYSTEM

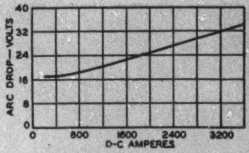


FIG. 6—ARC DROP CURVE OF SECTIONAL RECTIFIER

tendency of the formation of a cathode spot with resulting arc back, at the junction between insulation and conductor.

The cathode is equipped with a quartz cylinder which extends above the bottom of the vessel. This not only protects the edge of the cathode from the cathode spots at the surface of the mercury, but acts as a guide for the mercury vapor and as a sediment trap. The condensed mercury in returning to the cathode does so outside the cylinder; any foreign matter, being lighter than mercury, floats on top and remains outside the cylinder. In returning to the cathode the stream of mercury is broken up by an insulated baffle suspended from the cylinder and thus is prevented from bridging the cathode insulator. This arrangement is shown in Fig. 3.

The scheme of excitation used is shown in Fig. 5. By using a copper oxide rectifier, the advantages of a d-c starting and excitation system are obtained, without the objectionable features of a rotating device. Before the arc is struck, practically the full potential is applied to the solenoid which depresses the ignition rod into the mercury. After the arc is drawn, the resistor in series with the ignition rod causes the greater part of the voltage to be impressed upon the excitation anode and the greater part of the excitation arc immediately transfers to that anode, without the provision of a separate supply. By properly designing the excitation supply equipment, ample voltage is available for the operation of the solenoid without a prohibitively high current or losses in the resistor after the arc is struck. The value of resistance and the characteristics of the copper oxide rectifier are so coordinated that a final current of less than 3 amp in the starting rod and 10 to 15 amp to the excitation anode is obtained. By the addition of the excitation anode a source of ionization is brought close to the anode shield opening, thereby eliminating any hesitancy to "pick up."

When the load on a rectifier suddenly is increased to a high value, voltage surges tend to appear. For any given load on a rectifier there is a given condition of vapor flow, vapor density, and ionization. Before the vapor density and ionization have had time to build up to the requirements of the heavy load, the arc tends to be unstable and the fluctuations in the conductivity of the arc, together with the inductance of the circuit, generate the overvoltages. Since the source of these surges is the arc path between anode and cathode, their prevention is accomplished best by connecting capacitors between each anode and cathode to compensate for the variations in the conductivity of this path. Although it is not necessary for surge prevention, low valued resistors are connected in series with the capacitors to smooth out the voltage wave and avoid objectionable harmonics.

Because a rectifier requires a highly evacuated vessel, and one containing only pure mercury vapor, the manufacturing technique differs radically from that usually employed in the construction of electrical machines. Extreme cleanliness must be practiced during the processes, and many of these processes must be carried out in a conditioned atmosphere. The accomplishment of a satisfactorily tight vessel has been aided greatly by modern welding methods. It is obvious, of course, that a reliable insulating seal is necessary for both anodes and cathodes. However, several types of insulating seals are now well known, any one of which is sufficiently reliable. The choice of seal used is thus a matter of manufacturing convenience and cost. Seals used in the rectifier described here are the soldered-to-porcelain seal at the anodes, and a steel-protected rubber gasket at the cathode. A similar type of rubber gasket is used between main tank and cover.

Even with the best manufacturing technique, the construction of a nearly perfect metal vacuum tank is a difficult problem; and the difficulties multiply with size of tank. Herein lies an important advantage of the sectional rectifier: Not only is the size of tank small for a large capacity rectifier, but also the standardization upon one size always makes for higher quality and greater uniformity of product.

### AUXILIARIES

The system of auxiliaries used incorporates several unique features. The mercury vapor vacuum pump is of the multi-stage type, which is capable of pumping against a high back pressure. This high back pressure capacity permits the use of a barometric seal, which consists of a tube of barometric length with the lower end immersed in a pool of mercury; in case of any accident to the vacuum system, this arrangement acts as a perfect automatic valve and prevents admission of high pressure gases into the rectifier vessel. This barometric seal is incorporated in the interstage reservoir between the low and high pressure pumps, which permits intermittent operation of the high pressure pump. This pump consists of a rotary oil-sealed pump of small size directly connected to a $^{1}/_{4}$-hp motor. Because of the absence of gearing this pump is almost noiseless, and because of its small size the losses are low. However, the capacity is ample for the service required as is evidenced by the fact that in practice this pump is required to operate only from a few minutes per day to a few minutes per week depending upon how long the rectifier has been in service. The starting and stopping of the pump is controlled by a mercury manometer connected to the interstage reservoir. Since the pressure at which this pump starts is well below the maximum back pressure against which the mercury vapor pump will operate, a rise of pressure in the rectifier tank, with the resulting damage caused by operation under this condition, is not permitted.

The valve between the interstage reservoir and the rotary pump operates on a float principle and, therefore, is automatic without requiring any electrical connections. When the rotary pump stops, atmospheric pressure drives the oil back through the pump until enough accumulates in the valve to raise the float.

Pressure in the rectifier is measured with a manually operated gage of the McLeod type and also with a hot-wire instrument; the latter is connected to the control system for protecting the rectifier against operating under excessive pressures. This gage is not used to control the starting of the rotary pump because it is believed that operation of the rectifier with a pressure sufficiently high to operate this instrument is objectionable if continued for a long time. All pressure measurements are made at a connection to the tank separate from the pumping connection. At the low pressures being considered, there is a considerable variation in pressure along even relatively large passages. Therefore, a measurement made on a pumping section at some distance from the tank may indicate a pressure a great deal lower than actually exists in the tank. In the construction of the McLeod gage, a compressible chamber is used instead of the usual barometric tube, with a resulting reduction in length of more than 50 per cent. The hot-wire gage is of the familiar type, but has improvements in compensating features which reduce the effects of the various factors influencing its calibration.

### APPLICATION

With sectional construction the possibility of operating with part of the units out of service radically reduces the amount of spare capacity required in a high capacity installation. The manner in which the rectifier sections are assembled is quite flexible and is determined by the type of service required. In the rectifiers being supplied for the New York City Board of Transportation the sections are assembled in a truck type frame, and each section is made complete in itself with its own vacuum and water control systems. It is equipped with truck type contacts and flexible water connections so that one section can be disconnected in a few seconds, and the remainder of the unit continued in operation. This complete flexibility, of course, is obtained at the expense of increased cost and increased number of auxiliary parts with the inevitable increase in such troubles as originate in auxiliaries. However, the auxiliaries have been made so reliable that trouble from this source is not serious. Where extreme flexibility is not required, it is just as feasible to connect the rectifier sections to a common manifold with one pumping system, in which case the number of auxiliaries is essentially the same as for a single tank unit.

Since iron is the only inexpensive metal that does not react with mercury, metal tank mercury arc rectifiers are constructed of steel; this, together with the requirement for water cooling, introduces a corrosion problem. When water of the quality usually available is used directly, the rectifier must be designed so that all water spaces are accessible for cleaning and surfacing with corrosion resisting material; this maintenance must be performed at relatively short intervals. Another, and probably better, way of solving the corrosion problem is by providing a recirculating cooling system. This system may be either a water-to-water heat exchanger or a water-to-air heat exchanger. In either case the recirculating water may be such as to eliminate practically all corrosive action. The recirculating system may be either grounded and insulated from the rectifier, or connected directly to the rectifier and insulated from ground with rubber hose, depending upon convenience where installed. It is necessary, of course, that the temperature be controlled accurately. This is not a serious problem, however, for several types of direct-acting temperature-regulating water valves are available, and the control element is placed in the location of most rapid temperature change to avoid the overheating of any part before action takes place.

Mercury arc rectifiers are particularly adaptable for automatic or semi-automatic operation since the control and protective devices required are relatively simple. The degree of protection required depends upon the service to which the rectifier is applied; in many cases this can be reduced to provisions for: clearing a short circuit or arc back; preventing operation with excessive pressures due to a fault in the vacuum system; and preventing operation with excessive temperatures due to a fault in the cooling system.

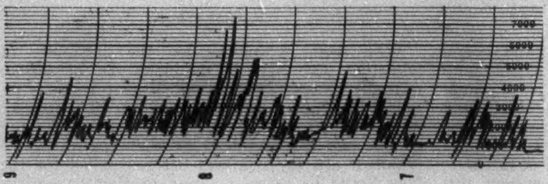


Fig. 7—D-C Load Chart of Rectifier at the Cedar Manor Substation of the Long Island (N. Y.) Railroad When Operating With Only 2 Sections in Service

The transformer connection used is influenced by the location where the rectifier is installed. The cost of a 12-phase transformer must be balanced against the additional cost of a harmonic filter to effect an equivalent wave with a 6-phase transformer, where wave form is important. Since both a-c and d-c systems are underground in the New York City Independent Subway System, and the telephone interference problem thus eliminated, a 6-phase transformer is being supplied for that installation because of its greater simplicity.

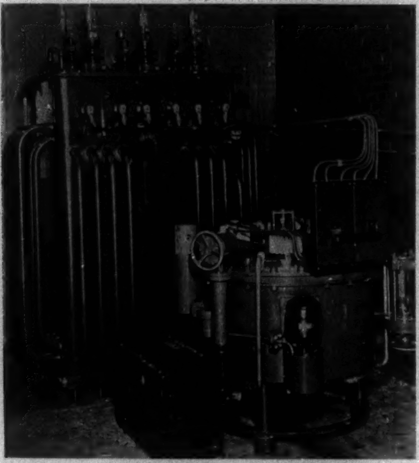
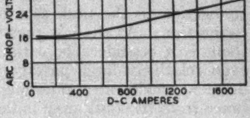


Fig. 8—Rectifier Section With Transformer Having a Capacity of 667 Amp Continuously With the Usual Overload Capacities; 34-In. Tank

The rectifier being supplied for the New York City, Board of Transportation, shown in Fig. 1, is rated 3,000 kw at 625 volts. Specifications require that it be capable of carrying 4,800 amp continuously, 7,200 amp for 2 hr, 9,600 amp for 5 min, and 14,400 amp for 1 min. This rectifier has demonstrated its ability to carry the specified loads, not only on the test floor, but also in actual service. Figure 6 shows the arc drop curve of this rectifier, which, of course, expresses the efficiency of the rectifier when the relatively small losses of the auxiliaries are added.

As mentioned previously, the design of the rectifier described here was based on a conventional design with which a great deal of service experience was available. Three installations were made of this type of design on 3 types of typical railway systems, and in all 3 cases essentially perfect performance was secured during several rectifier-years operation. To date, only one backfire has occurred on these rectifiers. After making the modifications discussed in this paper, in order to make this design suitable for sectional assembly, together with the improvements mentioned, a trial installation was made at the Cedar Manor substation of the Long Island (N. Y.) Railroad Company, early in September 1932. Two of these latest sections, as shown in Figs. 2 and 3, were substituted for 2 of the original sections shown in Atherton's paper (*loc. cit.*) and operation continued on the 2 new sections only. The remaining 2 original sections were kept out of service and maintained only as standby capacity. In this way by operating a station intended for a 3,000-kw rectifier on 1,500 kw of sectional rectifier capacity, a more severe test was obtained, and one more nearly in keeping with the rated capacity of the rectifier. Figure 7 shows a section of a daily load chart taken at this station. It may be seen that during the peak load period the base load averages more than the rated full load of 2,400 amp; upon this the usual short time railway peaks, up to 3 times rated load, are impressed. Up to the date of the present writing, 3 arc backs have occurred; in each case the rectifier was returned to service immediately. In addition to the outages due to arc back several minor interruptions have occurred due to auxiliary and control apparatus, but these have been few and the overall reliability has been equivalent to that required of electrical apparatus in general. Such weaknesses as have been disclosed in the auxiliary apparatus have been corrected. The cooling water consumption at this station has been extremely low. Because

Fig. 9—Arc Drop Curve of Rectifier Shown in Fig. 8



of the low load factor of a railway system and the high operating temperature employed, a large part of the losses is dissipated to the room.

### LOW CAPACITY RECTIFIERS

For application on loads of less than 1,250 amp, smaller units have been designed and built following the same general design as that of the sectional rectifier. A typical example is shown in Fig. 8. As would be expected from its smaller size, this unit has demonstrated that it will operate reliably over even a wider range of overloads than will the sectional units. It has a lower arc drop for the same percentage of normal load, as shown in Fig. 9.

### ACKNOWLEDGMENT

It is obvious that a development of this sort is not the work of any individual, but the result of the cooperative effort of many people. However, the present status of the development would not have been possible without the guidance and inspiration received from A. L. Atherton and J. Slepian.

## Discussion

**R. E. Hellmund:** Not only is the rectifier now the proper device for ordinary rectification in many cases where previously it could not compete with rotaries and motor-generator sets, but such applications as the regulation of induction motors with a rectifier in the secondary and many other possibilities previously suggested are coming closer to a practical and economical realization. In fact, with recent developments relating to the regulation and control of mercury arc devices, it seems that they are destined to play a most important part in all applications where appreciable amounts of power are involved. At the same time, it seems that the field of application of many electronic devices which have come with the advent of radio developments and with regard to the future of which many exaggerated and overoptimistic claims have been made, may be limited to smaller amounts of power, certain control problems, and some special applications. The necessity of heated cathodes in these devices and the limited life are, after all, appreciable handicaps. On the other hand, it seems that the future of the pool-cathode mercury arc devices, the development of which was originated in connection with power applications, is becoming brighter every day as the basic factors entering into their design and operation are becoming better understood.

**J. H. Cox:** The mercury arc rectifier now is definitely a developed piece of apparatus with reliability equal to or better than that of other commercial electrical apparatus; its efficiency has now been brought to a point where in many cases it is suitable for application on voltages as low as 230 volts; and its extreme simplicity in operation makes it admirably suited to automatic operation and permits a freedom of distribution of power supply not permitted with the rotary converter or motor generator. In this item the sectional type of construction has obvious advantages. In the electrochemical field the greater ease with which it may be protected from all effects of corrosive fumes makes it particularly valuable.

The advantages of the sectional rectifier have now been demonstrated. The space capacity presented is obvious, the efficiency is directly measurable, the reliability has been demonstrated in field service as well as laboratory tests and the advantage of the standardized small section from a manufacturing point of view has been even greater than anticipated.

Mr. R. E. Hellmund has mentioned the possibilities of the extended application to control uses; the prospects in this field are very bright.

# Communication

## ANNUAL REPORT OF THE COMMITTEE ON COMMUNICATION*

SOME of the advances in electrical communication were described in detail in technical papers sponsored by the Institute's committee on communication during the past year; others are outlined briefly in this report. Since it is desirable to keep the report short, only a few of the outstanding advances are mentioned.

A new type of telegraph repeater recently has been put into use to facilitate repeating multiplex telegraph channels individually into other multiplex circuits, which has the advantage of not requiring the maintenance of synchronism between the multiplex circuits concerned. An important application is a direct Montreal-London connection involving a Montreal-New York multiplex circuit and the 8-channel New York-London loaded cable. A multiplex telegraph channel concentration arrangement has been developed and installed in recent new telegraph offices. Operating positions, concentrated in the operating room, are connected through a switchboard located in the operating room to multiplex distributors grouped in the testing and regulating department. Reassignments of operating positions to meet changes in load readily are made, and important economies are effected in equipment, space, personnel, and other costs. There also has been developed a signal distortion indicating device for use in regulating and adjusting start-stop printer circuits without interrupting traffic. The device is of a stroboscopic nature and it indicates the effect of transmitter speed irregularities, relay bias, and other causes of signal distortion.

Successful experiments were carried out with a new method of superimposing telegraphy on telephony on the Madrid-Buenos Aires radiotelephone link. By means of inverters and spreaders in the telephone channel, and by appropriate allocation of frequencies, telegraphy at 125 words per minute was possible at the same time as speech.

Development of a new 18-channel voice frequency carrier telegraph system was completed and 3 of these systems have been installed in England. In this country trials of a 24-channel voice frequency system have shown that such a system is satisfactory from a technical standpoint.

During the year the British Post Office introduced person-to-person written communication service. This was called "Telex" service and is furnished to a subscriber over his telephone loop; he may talk or typewrite over the same connection, although not simultaneously.

In the United States an interesting development of teletypewriter service associated with telephone lines is the application of these devices to the direct printing of weather maps over extensive telephone plant networks for use in connection with airplane service. Outline maps are placed in the machines at airports connected to this system, and symbols transmitted from the U.S. Weather Bureau in Washington are recorded simultaneously at all of the stations in the group covered by one section of the weather map. These symbols show all of the regular items of the weather map.

To meet further demands for high-grade and economical circuits in cable, considerable development work has been carried out, including an extensive experimental installation of telephone carrier applied to a 25-mile loop of underground cable. A carrier system design has been achieved in which the difficulties due to enormously increased attenuation and increased tendency to crosstalk are surmounted. Sufficient work has been done to demonstrate that the system is entirely practicable. Carrier applied to cables offers important possibilities of economy, particularly for routes carrying heavy traffic. Telephone transmission improvement also is effected; this is particularly important for long circuits where, with present cable methods, transmission delays introduce difficulties. A paper on this subject was presented at the 1933 summer convention (see "Communication by Carrier in Cable" by A. B. Clark and B. W. Kendall, ELECTRICAL ENGINEERING, v. 52, July 1933, p. 477–81).

An interesting application of this method of cable transmission was made in recent experiments in high grade transmission of orchestra music. The new transmission system including pick-up arrangements, transmission lines, amplifiers, and loud speakers, represents a marked advance over systems previously developed for the transmission of music, in the following respects:

1. "Auditory perspective," that is for example, the reproduced sounds of different instruments of an orchestra appear to come from different parts of the stage, corresponding to the actual relative location of these instruments at the transmitting point.
2. Frequency spectrum covering practically the entire audible range, that is, from 35 to 15,000 cycles.
3. An intensity range corresponding to short-time energy differences between strong and weak passages of 10 million to one, making possible a volume of reproduced sound at least 10 times as great as that produced by the orchestra itself.
4. Increased control over the volume of sound at the receiving point and the relative loudness of various parts of the orchestra, making possible an enhancement of the musical effects over that produced by the orchestra itself.

Public demonstration of this system was made in Washington on the evening of April 27, 1933, with the Philadelphia Symphony Orchestra playing in Philadelphia. Transmission over the long distance circuits was so excellent that there was no appreciable difference in the overall characteristics of the system with or without the long distance lines.

The Italy-Sardinia submarine cable, the longest submarine telephone cable in the world (approximately 150 nautical miles) was completed and put in service. This continuously loaded cable, laid between Fiumicino, Italy, and Terra Nova, Sardinia, provides a single 2-way circuit on which are operated 1 composited duplex telegraph channel and 1 tele-

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***COMMITTEE ON COMMUNICATION:** H. S. Osborne, *chairman;* E. J. O'Connell, *secretary;* H. M. Bascom, W. H. Capen, A. A. Clokey, J. O'R. Coleman, C. F. Craig, R. D. Evans, W. L. Everitt, I. C. Forshee, C. M. Jansky, Jr., T. Johnson, Jr., G. M. Keenan, G. A. Kositzky, C. J. Larsen, J. R. MacGregor, John Mills, J. W. Milnor, C. W. Mitchell, P. H. Patton, F. H. Pumphrey, F. A. Raymond, H. A. Shepard, E. R. Shute, A. L. Stadermann, C. H. Taylor, H. M. Turner, and F. A. Wolff.

phone channel; it is designed for the addition of a 2-way carrier telegraph channel. Because of the long length and consequent high attenuation, special methods have to be used to achieve a high singing point in order to operate the circuit on a 2-wire basis.

Multi-party toll service or toll conference service was made available throughout the United States to a large portion of the telephone stations. Connections affording 2-way communication among not more than 6 parties are furnished immediately at the subscriber's request. For some of the more distant connections and those involving more than 6 parties, the service is being given on appointment where practicable.

A telephone cable between Kansas City, Mo., and Dallas, Tex., was completed during 1932, thus connecting Dallas and other Texas points into the toll cable network which now provides a storm-proof system covering most of the eastern half of the United States. Among other circuits this cable includes direct New York City-Dallas circuits, 1,850 miles in length, which are the longest direct all-cable telephone circuits in the world.

Micro-ray radiotelephone equipment is being built for the British Air Ministry and will be erected at Lympne, England. This will operate on a wave length of 15 cm in conjunction with similar equipment to be situated at St. Inglevert aerodrome, near Calais, France. This is the first commercial application of the micro-ray system. An interesting feature of this new service will be the use of teleprinters for transmitting and receiving messages.

A new technique of grinding tourmaline crystals makes it possible to produce such crystals commercially for wave lengths as low as 5 m.

Several new types of direction finders for ships have been developed, one of which incorporates an automatic indicator showing the bearings of the station at any time. The new direction finders need no correction as the quadrantal error is eliminated permanently by suitable design of the loop and antenna systems.

A considerable number of aircraft, formerly having only 1-way equipment for receiving beacon signals and weather reports, now have been equipped with 2-way radiotelephone equipment. Experiments on blind flying by means of directional radio signals have been continued with excellent results. By means of equipment on the aeroplane which indicates very accurately the landing runway and the altitude of the plane, it is now possible to land safely when the pilot is unable to see the ground.

The use of high power vacuum tube amplifiers in sound recording has made possible the development of an improved vertically cut record. Less inherent distortion, greater volume range, and a playing time of 15 to 20 min on a 12-in. record are possible with the new process. By using a reproducing stylus of very light weight, the records last for several thousand playings with no noticeable deterioration.

Experiments with the use of highly accurate frequency standards in connection with the control of power system operations are being made. The frequency standards, having their source in quartz crystal oscillators, are supplied to the control mechanism over telephone circuits.

In its a-c electrified territory one of the railroads has installed a neutralizing wire in its telephone conduit system connected to the track and substations through impedance bonds, and an aerial tape armored telephone cable for the mitigation of inductive interference; the results are highly satisfactory.

In nearly all municipal fire alarm systems that have been remodeled during the past year, copper oxide rectifiers, supplied with alternating current at 110 volts, have been used as sources of power.

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# Electrical Machinery

## ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

DURING the current year the Institute's committee on electrical machinery has functioned, as previously, through 5 major subcommittees, namely: synchronous machines, induction machines, d-c machines, transformers, and mercury arc rectifiers. These subcommittees have continued their activities in following the preparation of standards, in reviewing progress and development of the art, and in examination of papers offered for presentation at the stated conventions of the Institute.

Noteworthy advance has been made by the committee in recommendations for impulse testing of transformers and in revision of low frequency dielectric tests for transformers. A preliminary report on a test code for synchronous machines has been printed. Active progress is being made in the development of methods and testing devices for determining load losses and input-output efficiency of induction motors, as a preliminary to formulating a test code for induction machines. A test code for d-c machines is in preparation.

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*COMMITTEE ON ELECTRICAL MACHINERY: S. L. Henderson, *chairman;* P. L. Alger, B. L. Barns, E. S. Bundy, H. E. Edgerton, J. E. Goodale, T. T. Hambleton, J. L. Hamilton, A. L. Harding, C. F. Harding, E. W. Henderson, L. F. Hickernell, J. Allen Johnson, J. J. Linebaugh, H. C. Louis, W. V. Lyon, A. M. MacCutcheon, O. K. Marti, V. M. Montsinger, S. H. Mortensen, R. W. Owens, R. H. Park, E. B. Paxton, H. V. Putman, K. A. Reed, O. E. Shirley, F. V. Smith, R. G. Warner, and C. A. M. Weber.

Among the technical papers reviewed and accepted by the committee during the year are many important contributions in the fields covered. A brief outline of notable advances and progress during 1932 in the field of electrical machinery follows:

### SYNCHRONOUS MACHINES

A considerable part of the work on synchronous machines during this past year has been the improvement of details of design and manufacture. Progress has been made in high voltage coil insulation and in the reduction of fixed and stray load losses of high speed machines.

There has been no increase in the size of turbine driven alternators since the 1931 report. The 2 200,000-kva 1,800-rpm machines (GE)[1] in the Brooklyn Edison Company's plant have operated for some time and heat rate tests made on both machines show results better than the guarantees. A 183,333-kva 165,000-kw 1,800-rpm single-element turbine alternator (W) is being built for the Philadelphia Electric Company. This generator has 2 stator windings and is cooled by external propeller type blowers. A 166,666-kva single-shaft turbine alternator (GE) has been delivered to the Chicago District Electric Generating Corporation. It also has 2 stator windings and is the largest machine shipped with the armature completely wound. The inside armature frame with the winding is arranged so it may be assembled within an enclosing casing which also houses the 4 separately driven ventilating fans and the surface air coolers.

Experience is being obtained with high voltage turbine generators. Eight units from 3 different manufacturers had an equivalent of 22 turbine-generator-years of service up to January 1933. A more detailed tabulation is given in Table I.

The maximum capacity of waterwheel driven generators has not been increased during the year, although preliminary designs for a generator in excess of the capacity of any generators previously built have been made in considerable detail. Mechanical improvement in the line of simplification of bearing oiling system and other details has been made on the waterwheel generators.

Developments in the field of synchronous motors include the first (GE) totally enclosed fan-cooled type, particularly designed for use in class *I*, group *D* explosive gas locations. The ventilating air enters at the driving end and passes over the inner shield, across the back of the stator punchings, and is discharged at the collector end. The collector rings are enclosed and excitation is provided by a motor-generator set. A number of synchronous motors were applied in municipal water pumping stations. The trend in these machines is toward high efficiencies and in one case, an 800-hp 900-rpm motor (W) had a guaranteed efficiency of 97.6 per cent. It is believed that the first synchronous motors to drive power house draft fans were supplied to the Hawaiian Electric Company. These motors were a 2-speed motor rated 300 hp at 600 rpm, and 700 hp at 900 rpm (W) to drive an induced draft fan and a 200-hp motor at 1,200 rpm (W) for the forced draft fan.

**Table I—High Voltage Turbine Generators**

| Year Placed in Service | Station | Unit No. | Capacity Kilowatts | Voltage | Manufacturer |
|---|---|---|---|---|---|
| 1928 | Powerton | 1 | 52,500 | 22,000 | GE |
| 1929 | State Line | 1 (3 generators) | 200,000 | 22,000 | GE |
| 1929 | Powerton | 2 | 52,500 | 22,000 | GE |
| 1930 | Powerton | 3 | 105,000 | 22,000 | GE |
| 1931 | Michigan City | 1 | 68,000 | 22,000 | W |
| 1931 | Waukegan | 5 | 115,000 | 18,000 | AC |

Part winding starting has found increasing use on synchronous motors where starting requirements are extremely heavy, such as on flour mill line-shaft drive and cement mill tube-mill drive. A recent installation of 5 250-hp 277-rpm and 1 600-hp 138-rpm synchronous motors (EM) for flour mill line drive, the first of its kind, utilizes 5 part-winding steps in the motor to secure proper motor accelerating characteristics. The part winding steps are arranged to provide starting torque in increments from 60 per cent normal torque to 175 per cent normal torque. These torque steps are secured either manually or automatically to insure smooth starting without belt slippage.

A 60-kva 1.0-power factor 4,800-cycle 3-phase generator (GE) represents an advance in the use of high frequency for industrial heating. Two 60-kva 1.0-power factor 4,800-cycle single-phase generators (W) are now being built.

The 2 30,000-kw frequency changers (GE) at the Richmond Station of the Philadelphia Electric Company are now supplying single-phase 25-cycle power to the main line electrification of the Pennsylvania Railroad between New York and Philadelphia.

### INDUCTION MACHINES

The use of totally enclosed motors and especially the use of totally enclosed fan-cooled motors has increased considerably. An increasing demand is being experienced for splash or hose-proof motor construction. These machines are built suitable for outdoor installation, use in dairies, or where a hose is used in cleaning up the floors. A movement is underway to revise the definitions of the various types of enclosures.

The use of motor-reduction units has increased materially. This apparatus has been defined as follows: A motor-reduction unit is a motor with an integral mechanical means of obtaining a speed differing from the speed of the motor.

An outstanding development in the fractional horsepower single-phase motors has been first, the development of capacitor-start capacitor-run single-phase motors, employing usually a transformer and a paper condenser, and more recently, the development of capacitor-start induction-run single-phase

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[1] Manufacturer designation:
AC—Allis-Chalmers Manufacturing Company
BB—American Brown Boveri Company
EM—Electric Machinery Manufacturing Company
GE—General Electric Company
W—Westinghouse Electric and Manufacturing Company

### Table II—Mercury Arc Rectifier Units Placed in Operation During 1932 or on Order December 31, 1932

| Purchaser | No. of Sets | D-c Volts | Kilowatts Per Set | Total Kilowatts | Type of Control | Service | Placed in Service | Manufacturer |
|---|---|---|---|---|---|---|---|---|
| I. G. Farbenindustrie for Standard Oil Co. of Louisiana | 1 | 3,500<br>9,600 | 2,200 | 2,200 | Manual | Electrochemical | 1932 | BB |
| Long Island Railway Co. | 4 | 650 | 3,000 | 12,000 | Automatic | Railway | 1932 | AC |
| N. Y. Board of Transportation | 9 | 625 | 3.000 | 27,000 | Automatic remote control | Subway | On order | W |
| N. Y. Board of Transportation | 13 | 625 | 3,000 | 39,000 | Automatic remote control | Subway | *1932 | GE |
| N. Y. Board of Transportation | 15 | 625 | 3,000 | 45,000 | Automatic remote control | Subway | *1932 | GE |
| N. Y. Board of Transportation | 13 | 625 | 3,000 | 3,900 | Automatic remote control | Subway | *1932 | GE |
| Philadelphia, City of | 2 | 630 | 3,150 | 6,300 | Manual | Railway | 1932 | AC |

* Installed ready for service.

### Table III—Mercury Arc Rectifier Units: Comparison 1931–1932

| | 1932 | | 1931 | |
|---|---|---|---|---|
| | No. of Sets | Kilo-watts | No. of Sets | Kilo-watts |
| Placed in service | 48 | 143,500 | 57 | 127,845 |
| Being installed | | | 14 | 41,200 |
| On order | 9 | 27,000 | 34 | 102,300 |
| Grand total for year | 57 | 170,500 | 105 | 271,345 |
| Total number units in service, Dec. 31st | *228 | 448,879 | 180 | 305,379 |

* Includes 41 units installed and ready for service.

motors, employing a low voltage condenser of relatively large capacity for starting purposes only. The low voltage capacitor-start single-phase motor is finding its first application in the household refrigerator field.

The greatly increased activity in the air conditioning field has resulted in motors being developed to operate fans, blowers, and water agitators, which are quiet and have long life of bearings.

Dual motors, alternating and direct current on one shaft, have been developed to meet the requirement of refrigerating trucks and railroad cars and air conditioning passenger cars. The d-c motor is used to drive the refrigerating machine when the truck or car is in motion, the current being supplied from the d-c generator on the truck or car, and the induction motor is used when the truck or car is standing, the motor being connected to the a-c city distribution system.

## D-C Machines

The largest 350-rpm d-c motors so far constructed are reported for the current year. Six 3,500-hp 175/350-rpm d-c motors (AC) were placed in service on 6 finishing stands of a 76-in. continuous-strip mill, power being supplied by 3 5,000-kw 3-unit motor-generator sets. Three 3,500-hp 175/350-rpm d-c motors (GE) were placed in service on the finishing stands of a 72-in. continuous hot-strip mill for the Otis Steel Company, power being supplied by 2 4,000-kw 3-unit motor-generator sets.

A light weight d-c generator (W) has been completed. It consists of 3 units, one rated 8-kw 115-volts and 2 rated 2.5-kw 3,000-volts at 2,200 rpm. Two bearings are used, mounted in cast magnesium brackets. Total weight of the machine is 549 lb.

A gas electric "crawler" type track welder (W) has been completed. This machine is designed with low head room to move along the shoulder of the road bed, so as to clear the rolling stock and furnish power for building up worn rail ends by arc welding, and in addition, to furnish power for a grinder and nut tightener. A series motor taking power from the welding generator is used to move the welder along the track.

## Transformers

The activity of the transformer subcommittee in developing standards for the commercial impulse testing of power transformers has borne fruit in an agreement upon a tentative test code. This test procedure, including a program of applied impulse tests made with the transformer excited, was presented at the Institute's 1933 winter convention in a paper by Messrs. Vogel and Montsinger. Meanwhile the ranks of the manufacturers prepared to make commercial surge tests have been augmented by the installation by Allis-Chalmers of a high capacity surge generator capable of delivering 2,000,000 volts, with complete cathode ray and pontentiometer equipments and arrangements for synchronizing the impulse with the peak of a normal frequency alternating voltage wave. Commercial surge tests have been applied to transformers with such ratings as 20,000 kva, 132 kv (GE); 2,000 kva, 69 kv (GE); 4,500 kva, 132 kv, 25 cycles (GE); 20,000 kva, 230 kv (W); 20,000 kva, 132 kv, 25 cycles (W); 10,000 kva, 132 kv (W); 4,500 kva, 132 kv, 25 cycles (W); and 20,000 kva, 115 kv, 3-phase autotransformers (W).

Four of the largest 230-kv single-phase transformers yet constructed have been built (GE) with ratings of 45,000 kva self-cooled and 60,000 kva with air blast. With a total weight of 393,000 lb, it was necessary to ship them in nitrogen in special low slung tank cars.

Transformers have been supplied (AC) with a low pressure system for automatically maintaining inert gas protection without chemicals or moving mechanical parts. The system involves an oil seal in an expansion tank which isolates the inert gas from the atmosphere and permits considerable change in oil level in the main tank with slight change of pressure.

In the field of load ratio control, a new type *UT* tap changer (W), smaller and less expensive than its predecessors, applicable to small transformers and capable of operation under short circuit, has been actively supplied. A quick operating automatic tap changer (AC) has been developed for large distribution and small power transformers up to 15 kv. Two 40,000-kva 3-phase regulating transformers (W), simultaneously controlling regulation of phase angle and voltage, were installed in New York. A self-contained automatic step voltage regulator (GE) is available for 3-phase rural circuits of 50 amp at 4,800 to 13,800 volts.

Self-contained surge-proof distribution transformers employing de-ion gaps (W) have been extended to the 4,800 and 6,900 volt classes. The line of self-protecting stud-type-bushing distribution transformers (AC) has been supplemented with provisions for mounting surge diverters either internally or externally.

Pyranol (GE) and inertol (W) non-inflammable non-explosive mediums, developed to replace mineral oil where other methods of preventing fires are not practicable, have been developed and applied to low-voltage network transformers.

### MERCURY ARC RECTIFIERS

Tables II and III give general data on mercury arc rectifier activities during the year. Nine of the 3,000-kw 625-volt sectional rectifiers (W) mentioned in last year's report were ordered by the New York Board of Transportation.

An innovation in the rectifier field was the equipment of a standard 3,125-kw 625-volt railway rectifier with automatic grid voltage control (AC). A constant d-c voltage is held independent of load and supply voltage variations.

Ten of the New York Board of Transportation 3,000-kw rectifiers (GE) were placed in service, supplying power for the operation of the 8th Avenue Subway, New York.

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# Electrochemistry and Electrometallurgy

## ANNUAL REPORT OF THE COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY*

WHILE the engineering and research activities of many organizations have been curtailed considerably during the past year, several developments have been brought forward which are worthy of record. Those which have been brought to the attention of committee on electrochemistry and electrometallurgy are mentioned briefly here.

### HIGH TEMPERATURE STEEL TREATING FURNACES

Development work is being carried out actively to meet the increasing demand for industrial furnaces in steel treating work where temperatures of 2,000 to 2,500 deg F are required. Inductive methods of heating in some cases work out very satisfactorily; in other cases, resistance heating, either by direct conduction or by radiation, will meet the requirements better. There is a definite field for the electric furnace in this temperature zone, and progress is being made in filling it satisfactorily.

### ELECTRIC FURNACE IRONS

The term "electric steel" has denoted for a long time superior steels made in the electric furnace. The comparatively new term "electric furnace iron" denotes superior grades of cast irons which are the products of the electric furnace. The main feature in the production of these irons is the heat treatment of the molten metal at temperatures beyond the range of the cupola. These new irons are marked by high tensile strength and uniformity. The growing demand for these products of the electric furnace is enlarging materially the field of electric heat for producing molten metal.

### LITHIUM

The production of lithium now has been established on a commercial basis in this country. This metal is being used as a hardener for aluminum and lead alloys. It is being used also as a superscavanger in ferrous and non-ferrous metal production, and in the degasification of copper. The latter application is of special importance to electrical engineers in connection with the manufacture of high conductivity copper.

### PROCESS REGULATION

Manual control of hydrogen ion concentration in flotation, electrolytic reduction, and refining plants is expensive, slow, and inaccurate. Two schemes have been worked out for the automatic regulation or control of hydrogen ion concentration which employ

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photoelectric tubes in such a manner as to avoid errors caused by line voltage variation, temperature variation, or changes in tube characteristics with age. Both of these schemes supply an adjustable inoperative time during which a correction is allowed to take effect before the regulator is permitted to attempt a second correction. This equipment should find application not only in the control of hydrogen ion concentration but in control of color or opacity of a solution which is affected by a single varying chemical.

Accurate control of high temperature has been made possible by the development of a high temperature indicator and regulator employing the electrical conducting characteristics of certain refractory materials at high temperatures. The refractory material receives radiant energy direct from the material whose temperature is to be regulated, and thus the resistance of the refractory material is proportional to the temperature. The material is placed in a bridge circuit which is balanced for the desired temperature or resistance of the refractory material. Any deviation from this temperature, of course, unbalances the bridge circuit and the unbalanced current is amplified and used to control the power input to the furnace in order to bring the temperature back to the desired value.

Operating power costs have been decreased by the application of power regulators to improve the load factor of a plant. In electrolytic plants it has proved practicable to raise the load factor to 100 per cent thus obtaining a minimum power cost for producing a given amount of product, since the total kilowatthours are regulated to equal the past average kilowatthours.

Electrolytic cell efficiencies have been increased by the application of constant current regulators, maintaining the cell circuit at the optimum value of current considering both efficiency and production requirements.

### Electrical Precipitation

In addition to those fields of application where electrical precipitation processes have been used in the past, these processes have recently been adapted to problems of gas cleaning in iron blast furnace and paper mill operations.

Progress has been made in the development of hot cathode vacuum tubes for high voltage rectification for electrical precipitation. Voltages up to 100 kv have been successfully rectified, though this is in excess of the normal requirements for precipitation, which does not exceed 75 kv. The field for high voltage rectification is not confined to electrical precipitation, for X ray applications, cable testing, and electrostatic separation schemes all require such a supply.

### Electrolytic Hydrogen

During 1932 a 6,500-kw 650-volt mercury arc rectifier was put into service for producing hydrogen by electrolysis. This rectifier consists of 2 3,250-kw tanks operating from one transformer. A primary regulating transformer provides a range in the d-c voltage from 600 to 670 volts. This equipment is used in a new atmospheric nitrogen fertilizer plant, and has been in successful operation for about a year.

### Electricity in Chemical Processes

Application of electricity to chemical processes was reviewed by Dr. Colin G. Fink in an address which proved to be the salient feature of the session sponsored by this committee at the 1933 winter convention. In this address Doctor Fink presented much valuable data relative to the use of electrical power in chemical and metallurgical industries. The address having been published in the March, 1933, issue of Electrical Engineering (p. 151–4) no repetition of the data is included in this report.

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# General Power Applications

## ANNUAL REPORT OF THE COMMITTEE ON GENERAL POWER APPLICATIONS*

ALTHOUGH industrial activity as a whole was at a low ebb during 1932, a considerable amount of development and rehabilitation work was carried on by certain industries. Industries are broadly classified as those producing capital goods and those producing consumption goods. During a depression there is little demand for new construction and capital goods but the demand for consumption goods remains fairly constant. There will probably be little demand in the near future for the expansion of plant capacity but it is evident that many existing plants must be remodeled and brought up to date if they expect to meet competitive conditions. Of the companies manufacturing consumption goods many have already appreciated that with the narrowing margin of profit their position and success depends very largely on the continuous reduction of their manufacturing costs and improvement in their product. The trend of the times is consequently toward increased economy of production and improved process control resulting in a better product at a lower cost and it is along these

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lines that the industrial engineers are working at the present time. It was consequently the opinion of the Institute's committee on general power applications that papers requested or sponsored by it should as far as possible present material which would be helpful and of value along the above lines.

The committee sponsored a session at the 1932 winter convention of the Institute at which 3 engineering papers were presented together with an introductory address by Crosby Field (A'14, F'22) entitled "Economic Conditions and the Engineer." The latter was published in full in the March 1933 issue of ELECTRICAL ENGINEERING, p. 149–51, and presents some very interesting and instructive comments on our present economic situation. The technical papers presented at the convention were as follows:

VARIABLE VOLTAGE OIL WELL DRILLING EQUIPMENT, by A. H. Albrecht

RECENT DEVELOPMENTS IN ELECTRONIC DEVICES FOR INDUSTRIAL CONTROL, by F. H. Gulliksen

CIRCUIT BREAKER PROTECTION FOR INDUSTRIAL CIRCUITS, by H. J. Lingal and O. S. Jennings

Instead of attempting to abstract information regarding the numerous developments in industrial apparatus or regarding industrial applications the committee feels that members interested in such equipment can readily obtain such information directly and more completely from the various periodicals, but the committee does desire at this time to indicate the trend or nature of some of these more important developments.

### GEAR MOTORS

During the last year there have been placed on the market a large variety of makes and designs of gear motors and these are being extensively used in industries on account of the saving in space effected, their higher efficiency, and reduced maintenance as compared with open gear or belt drives.

### ELECTRONIC CONTROL

Although the possibilities of electronic control in various industrial applications have been appreciated for some time there was a marked increase during the last year in the available equipment such as various assemblies of photoelectric relays and special devices. The paper presented at the winter session indicates some of the advantages and possibilities for such equipment in industrial service. Besides the speed and accuracy of electronic equipment together with the freedom from mechanical friction and maintenance, numerous applications have been found where existing types of equipment could not be used and solutions are possible only by means of this newer class of apparatus.

### AIR CONDITIONING

A large amount of engineering attention is being devoted to the possibilities of air conditioning, especially in connection with households, offices, and transportation equipment, and in some cases such air conditioning equipment is being combined with heating equipment and more especially with the oil burning automatic type.

### MOTOR PROTECTION

Although fan cooled and explosion resisting motors have been previously mentioned, the advantages of such equipment are being more widely appreciated and many such motors are being installed in the open without protection from the weather whereas previously special housing and protective equipment was necessary. One of the most recent developments in connection with motor protective devices is a thermostat which is mounted on the motor so that when the temperature reaches an excessive value either a signal is given or the motor is shut down depending on how the thermostat is connected. This motor thermostat supplements the standard thermal relay protection and the combination of the 2 devices protects against all forms of motor overload.

In conclusion it is desired to emphasize the fact that few of the developments in industry are large or spectacular but it is the steady introduction and application of these new ideas and developments which keep an industry up to date. The fact that many plants have not pursued this policy accounts for the large amount of obsolete equipment in industry at the present time and the large expenditures which it has been estimated are required for rehabilitation in order to modernize the various industrial plants so that they can manufacture on an economical basis.

# Instruments and Measurements

## ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

DURING the year 1932–33, the A.I.E.E. committee on instruments and measurements consisted of 23 active members, (see footnote) representing various phases of the electrical industry interested in electrical measurements. The active work of the committee was taken care of through 7 subcommittees organized as follows: instrument transformers, indicating instruments, telemetering, high frequency and sound measurements, temperature measurements, definitions of instruments and testing, and measurement of transformer exciting current. Activities of these subcommittees are summarized in the first portion of this report.

### Instrument Transformers

The subcommittee on instrument transformers was engaged in completing the revision of the Standards for Instrument Transformers. The report made at the October meeting of the committee was accepted and the standard circulated to the members for letter ballot. The result of this ballot indicated that almost all the members were ready to approve the revision with certain minor changes. These are being made, and the revision will be submitted to the A.I.E.E. standards committee for acceptance.

This standard has entailed considerable work on the part of the subcommittee, and led to rather wide discussion of suggested changes in the definition of "phase angle for instrument transformers," which later was taken up by the standards committee.

### Indicating Instruments

The Indicating Instrument Standards No. 33 has been under consideration for revision by this subcommittee. The work was advanced to the stage where a draft was circulated to the membership of the main committee for comment. Based upon the replies, an approved draft now is being prepared and will be ready at an early date for submission to the standards committee.

Recently the American Standards Association appointed a sectional committee to consider the adoption of the Institute standards as an American standard. It is expected that the revised issue will be the basis for discussion by this sectional committee on which the instruments and measurements committee has 3 representatives.

### Telemetering

The subcommittee on telemetering during the past year has devoted its work primarily to following new developments in its field. At the summer convention in 1932, it submitted, in coöperation with the automatic stations committee, "A Report on Telemetering, Supervisory Control, and Associated Communication Circuits" (see Electrical Engineering, v. 51, September 1932, p. 613–20). This report is a comprehensive survey of available systems, and will serve as a standard of reference for several years.

### High Frequency and Sound Measurements

The subcommittee on high frequency and sound measurements is working with a committee appointed by the Standards Committee to draft definitions and standards for sound measurements. Through the efforts of this subcommittee, an informal session on sound measurements was held during the 1933 winter convention, and at the summer convention a paper on that subject was presented representing the progress in that field to date. Activities in the field of high frequency measurement were outlined by this subcommittee, but, because of present conditions, completion of several intended studies was delayed. This work had to do with measurements of resistance, voltage, and current.

### Temperature Measurements

Work planned by this subcommittee included the preparation of a standard code for temperature measurements. Considerable data have been collected, but will require additional study before the preparation of a tentative draft. It is expected, however, that during the coming year this work will be completed and made available for the Institute.

### Definitions of Instruments and Testing

As reported last year, the work of this subcommittee was completed and these definitions submitted to the working committee. Since that time, the definitions have been published. It has been recommended recently that several terms that have not been defined in these definitions be included; these definitions are to be presented to the working committee for their consideration.

### Measurement of Transformer Exciting Current

The transformer subcommittee of the electrical machinery committee transmitted to the instruments and measurements committee a request to prepare suitable methods for measuring exciting current of transformers when excited with other than pure sine waves. The subcommittee on measurement of transformer exciting current undertook this work and reported a suitable procedure at the April meeting; this was adopted and has been forwarded

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to the transformer subcommittee for their use. The report includes a recommended method, but also discusses other methods available and their limitations.

### Review of A.S.M.E. Code

In addition to the foregoing work, the instruments and measurements committee reviewed a test code prepared by the American Society of Mechanical Engineers dealing with electrical instruments. This work was speedily completed and approval given so that A.S.M.E. could undertake publication of this material, which already was in final proof form. It was brought to the attention of the standards committee that it would be desirable to arrange to have the A.S.M.E. refer to A.I.E.E. standards and codes for such information rather than prepare their own publications in this field. It is understood that this suggestion has received favorable consideration.

### Future Work

In addition to the present activities, a suggestion was made that the instruments and measurements committee undertake the study of methods for surge voltage measurements. This suggestion is an outcome of papers presented under the auspices of the committee at the 1933 winter convention, and the ensuing discussion.

Considering conditions that exist, the work of the instruments and measurements committee has shown hardly any curtailment. It is felt that such activity is a result of the efforts of the vice-chairman, the secretary and the chairmen of the subcommittees who have carried on their work so that several important projects have been completed. There is no doubt that the present membership of this committee is an active one and of sufficiently broad connections so as to be productive of further good work in the future.

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# Iron and Steel Production

## ANNUAL REPORT OF THE COMMITTEE ON IRON AND STEEL PRODUCTION*

IN NO YEAR since electrification gained a foothold in the industry, has there been so little activity in main roll drive equipment. When the industry is operating at 15 per cent of capacity there is no justification for the comparatively large expenditures involved in the installation of new mills. However, periods like the present emphasize the need for reducing costs wherever possible; in many instances expenditures for modernizing auxiliaries have been more than justified even at present production, for the resultant saving.

The main roll drives installed during the year consist of: a 3,000-hp 6,600-volt 60-cycle motor driving a sheet bar mill; a 500-hp 2,200-volt 60-cycle motor driving a 10 in. merchant mill; a 1,000-hp a 600-hp and 2,400-hp d-c motors driving cold roll mills and 1,200-hp and 600-hp motors on cold roll strip mills.

The sheet and tin section of the industry seems to be going through a violent awakening, and has shown much activity, evidenced by the installation of automatic furnace and catcher equipments, cold strip mills, continuous gaging equipment, automatic length measuring apparatus, bright annealing furnaces and so forth.

A considerable number of automatic catcher equipments for sheet mills have been installed. Due to the extremely rapid operating cycle on these devices, requiring the driving motors to reverse up to a maximum of 40 times per minute, it has been necessary to develop special motors and control equipments. The majority of these equipments have employed fan cooled squirrel cage a-c motors, but for some mills adjustable speed, d-c motors have been used.

While automatic catcher equipment for 2-high mills was first introduced a year or 2 ago, automatic and manually controlled equipment was developed this year for the 3-high sheet mills.

In this field the photoelectric tube has been applied in some cases as a limit switch to control the automatic operation of the catcher equipment. It has also been used in connection with a pack measuring device consisting of a Selsyn generator geared to the mill and a Selsyn receiver connected to a pointer revolving about a dial to give automatically, a fairly exact indication of the length of a sheet after each pass. This indication permits faster rolling, increases of from 5 to 10 per cent having been reported where adequate heating capacity is available. It also reduces the scrap percentage because it indicates to the roller after each pass, what elongation has been effected during that pass and finally indicates on the last pass, whether or not the pack is long or short.

Catcher motor and control equipment is undergoing continual improvement. Motors can be supplied taped for several combinations of winding producing various values of torque and rates of acceleration and deceleration. When rolling loose packs it is necessary to artificially slow up the rates of acceleration and deceleration of the chain conveyor motors and this can be accomplished either

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by the above mentioned method of changing the motor winding, through a semipermanent 3-phase resistor in the motor circuit or by a saturable reactor in the common circuit of the 2 chain conveyor motors. Each phase of this reactor will have an a-c and d-c winding and the reactor is designed to develop a high value of reactance when the d-c circuit is open. When either the forward or reverse contactors close, d-c excitation is applied to the reactor. The effective reactance of the reactor then decreases as the direct current builds up in the excitation winding. By varying the strength of this current with an adjustable rheostat, the time of reversal can be readily adjusted from 3 to 10 cycles to allow the maximum speed of reversal without slippage; that is, if a motor ordinarily reverses in 10 cycles this device permits increasing the time from 13 to 20 sec. The chief advantage of the reactor method over the resistor method is that the slow down is readily adjustable.

Automatic tension reels have been applied in wire plants where a squirrel cage motor was designed to operate beyond the peak in the torque curve; that is, as the slip increases the torque from the motor decreases. When the reel is approaching its filled point, the torque delivered from the motor shaft is less at the speed required than when the reel is partially filled. This condition exists because the windage and friction at the higher speed plus the torque necessary to give the proper tension, requires a higher torque from the motor than that required to maintain approximately the same tension at the lower speed, with the increased lever arm.

The measurement and control of temperature during rolling operations, especially with alloy steels is an important factor in the gage or finish of material. The photoelectric tube pyrometer utilizes the radiation from the hot metal as indications of temperatures above 1,500 deg F. Relay devices can be actuated to perform whatever service is required.

Gear motors, consisting of standard a-c or d-c motors with built-in gear systems have been developed for light runout tables and similar applications. Thrustors, a device for producing straight line motion, continue to find new applications.

"Bell" type electric furnaces have been developed for bright annealing wire and strip of either copper, copper alloys, or steel. Continuous type furnaces for similar purposes have been built for material that represents bulk rather than weight. Atmospheres in either type are of a protective nature to prevent oxidation of the material being heated.

Development continues in the use of high frequency current, on the order of 1,000 cycles, for inductively heating materials for annealing, normalizing, or forging. The probabilities are that this method will gain in favor in the future, as the advantages in this type of heat treating and annealing are exploited.

A great number of devices and developments common to all industry are being used to advantage in the steel industry. Among them are control using gas or mercury vapor hot cathode electronic tubes for resistance welding of the intermittent type; de-ion grids for oil circuit breakers and ordinary safety switches; de-ion air circuit breakers rated as high as 1,200 amp., 7,500 volt, for main roll drives; X ray equipment for radiographic examination of thick sections of metal and numerous others of like importance.

Coated welding electrodes, which are now available in both rod and coiled form, for general as well as certain specific applications, have been improved to secure penetration with a lower current, thus avoiding the "spattering" known as undercutting.

While there has not been a great amount of progress in the exchange of power between steel plants and central stations, the margin between the costs of power generated from the by-product heat from the basic operations of steel making, and power generation by central station steam and hydroelectric facilities, has steadily narrowed. The probabilities for the future are toward the use of all possible available by-product heat in steel heating and treating operations and the purchase of power, rather than the generation of power from the by-product gases, and the purchase of auxiliary fuels for heating and treating operations.

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The committee submits a list of papers published by various sources which cover in detail many of the subjects mentioned in this report.

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3. MAIN ROLL DRIVE OF 30-IN.–21-IN. CONTINUOUS MILL AT BETHLEHEM STEEL CO.'S LACKAWANNA PLANT, F. D. Egan and C. B. Huston. *Iron & Steel Engr.*, Feb. 1932, p. 93–101.

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7. HOT ROLLING, COLD ROLLING, SINGLE STAND MILLS, CONTINUOUS MILLS, A. P. Steckel. *Iron & Steel Engr.*, Jan. 1933, p. 3–8.

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# Power Generation

## ANNUAL REPORT OF THE COMMITTEE ON POWER GENERATION*

FOLLOWING the intention announced in last year's report, the A.I.E.E. committee on power generation* continued to promote the discussion of matters in the field of electric power generation from a retrospective and generally analytical viewpoint, for the particular purpose of weighing recent tendencies in design to the end that profitable avenues of progress may be revealed and utilized when capital investment again is resumed on a hitherto normal scale in the construction of power-generating facilities. The committee does not believe that the present lull in construction activities should result in a stagnation of the directive thought that will be responsible for the design of power stations in the future, nor in the entire diversion of such ability to the problems of minor improvements and operation under reduced output, commendable and necessary as such duties may be. It is glad to report a very real interest among responsible engineers in the consideration of the major principles governing the economic generation of power, and to note that fundamental thought and work are being actively continued.

The committee calls attention in this report to 4 papers[3] presented at the 1932 A.I.E.E. summer convention, Cleveland, Ohio, that discuss current practices in the operation of power systems which include several generating plants. The success in the operating interconnection among a group of plants to supply a load area has been one of the notable achievements in the last decade in the field of power generation. These 4 papers summarize present ideas about the most effective methods of operating such systems to obtain maximum reliability in service and minimum operating cost. They also indicate a reduction in operating expenses on representative power-generating systems in the immediate past, and give assurance that the improvement in operating economy has not been at the expense of unjustified carrying charges.

A group of 4 papers[83,90,97,98] on hydroelectric power generation (presented at the Baltimore, Md., district meeting, in October 1932) included: a comprehensive survey of the economics of water power developments; analyzed the possibilities of the regenerative type hydroelectric plant; discussed the development of the latest design of water turbine; and described a recently constructed plant of large magnitude that contains the most powerful Kaplan turbines yet built and the largest in physical dimensions so far installed on this continent. A notable hydroelectric plant on the St. Lawrence River of unusual magnitude and incorporating novel features for the production and distribution of 25- and 60-cycle energy is discussed in a paper[81] presented at the 1933 summer convention.

The salient features and the economics of high pressure and high temperature steam-electric power plants were analyzed in a paper[39] presented at the 1933 winter convention. In the discussion mention was made of the modern method of fabricating pressure vessels by means of the electric arc.

Although the volume of generating plant construction is small in the plants that have been designed recently, contemporary ideas as to economy in investment and operation are developed to an extent that is probably in advance of anything hitherto attempted. Progress in the use of large boilers and turbines operating at 1,300 lb per sq in. and 850 deg F with a ratio of one boiler per turbine is exemplified by the Port Washington plant of the Milwaukee (Wis.) Electric Railway and Light Company. The design of this plant is described in a paper[30] presented at the 1933 A.I.E.E. summer convention. Another paper[42] presented at the same convention discusses the rehabilitation of a low pressure steam power plant on a large system, which had been practically retired except for peak service. This rehabilitation was accomplished by installing a turbine to operate with throttle steam at 655 lb per sq in. and 850 deg F, and to exhaust at pressures up to 220 lb per sq in. into the mains that supply the low pressure turbines. The compounding of the new turbine upon the old station has made an almost obsolete plant the most efficient on the system.

A subcommittee under chairmanship of F. H. Hollister has in preparation a symposium on the subject "Switching Energy at Modern High-Capacity Generating Plants," which is contemplated for presentation at the 1934 A.I.E.E. winter convention. Experience during the more recent years where particular generator, bus, and switching arrangements are used, will be analyzed, the limitations discussed, and the probable trends noted.

The committee recommends also that the subject of regenerative hydroelectric plants presents opportunity for the assembly of valuable experience derived in European plants. The use of this type of plant has been more extensive in Europe than in this country, but some engineers believe that the future will witness an increasing number of such plants in the United States.

The custom of the committee has been to prepare a detailed progress report and bibliography in its field at biennial intervals; the remainder of this report therefore summarizes matters of interest that have developed or culminated in the past 2 years.

## I—Volume of Power Generation

When the 1931 report of the power generation committee was written, the United States was suffering

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† Members of subcommittee on report.

[3] For all numbered references see bibliography.

from a 2 years' drought and a business depression. By the end of that year rainfall quite generally had become normal. From 1921 to 1929 the amount of power generated in public utility plants in the United States increased from 41 to nearly 97.5 billion kwhr, a gain of 138 per cent in 8 years. Since 1929 the volume of power generated has dropped to 84 billion kwhr, a decrease of 13.9 per cent in 3 years.

Beginning with 1928 to the end of 1931, hydro-generated power decreased from a maximum of nearly 35.0 to 30.6 billion kwhr, notwithstanding that during that period the installed capacity in hydroelectric plants increased over 2 million hp. Last year was a fairly good water year. Hydrogeneration increased to near the 1928 figure and represented a larger part of the total generation than for previous years, being 40.5 per cent. The increase in hydro-generated power with a decreasing total volume of generation has caused a heavy loss in output from fuel burning plants, a drop of 11.9 billion kwhr occurring during 1931 and 1932.

## II—Generating Plant Construction Progress

Although the volume of generation by utility plants has decreased 13.9 per cent in the last 3 years, installed capacity in these plants has increased 5 million kw, or about 20 per cent. The increase in steam plant capacity amounted to about 3.5 million kw, and in hydroelectric stations, to 1.5 million kw. This large capacity increase represents the completion of construction programs under way at the beginning of the depression. Work has been practically completed on most of the projects initiated within the past 2 years. The present total of central-station generating-plant construction budgets is lower than in any year during the last decade.

The steam-electric generating plant capacity added in 1931 was about 1/3 as great as in 1930 when over 2 million kw was placed in operation; in 1932 the new capacity was slightly smaller in amount than in 1931. The 1931 installations were about equally divided between existing plants and newly constructed plants; in 1932, additions to 3 major plants comprised practically the entire new steam plant capacity placed in operation. Only 2 new major steam plants are now under construction; large extensions that have been initiated to 2 existing steam plants are being postponed.

In the water power field, the new capacity initially operated in 1931 in the United States exceeded slightly that in 1930; Canadian installations in 1931 also were at or above normal volume. The decrease in added capacity in 1932 was very marked in the United States when the total of several small installations was only about 1/9 of the increase in 1931; the initial operation of the large Beauharnois plant in Canada resulted in new capacity there somewhat in excess of 1/3 of that in 1931. Only one important project, Boulder Dam, is actively under construction in the United States. There are several plants, totaling about 750,000 hp, on which work was started but has been postponed temporarily. Not one important contract for hydraulic turbines was let in 1932 in the United States and Canada, which is an indication of how seriously water power developments have been curtailed. This year the contract for the Boulder Dam turbines is the only major one to be placed. Unless work soon is started on some of the larger projects now being considered, hydroelectric construction probably will be of small volume for the next few years.

Photo by Arthur E. Cheesman, New York, N. Y.

One of the 2 160,000-kw tandem-compound turbine-generators installed in the Hudson Avenue station of the Brooklyn (N. Y.) Edison Company during 1932. The unit operates at 1,800 rpm, is 85 ft 8 in. long, 24 ft wide, and stands 24 ft above floor line

## III—Interconnection

While the interconnection of power systems already accomplished has continued to promote economy in power generation in the 2 years elapsed since the last report, but few additional notable interconnections have been established. A major one has been between the systems of the Niagara-Hudson Power Company (N. Y.) and of the companies affiliated with the Consolidated Gas Company in New York City. This interconnection, which has been described in *Electrical World* of July 18, 1931, consists essentially of 4 110-kv circuits extending from the Mohawk Valley to a switching station at Pleasant Valley, about midway between Albany and New York City, at which point the voltage is changed to 132 kv. From Pleasant Valley 2 132-kv circuits will extend into the New York City system through existing 132-kv underground cables. The Pleasant Valley transformation is by means of 2 banks of auto-transformers, each having a capacity of 100,000 kva. Synchronous condensers are connected to tertiary windings in these transformers. The parties to this interconnection expect to realize a saving in generating capacity requirements by the exchange of emergency service. Also, economy flow and storage power transactions will be made possible.

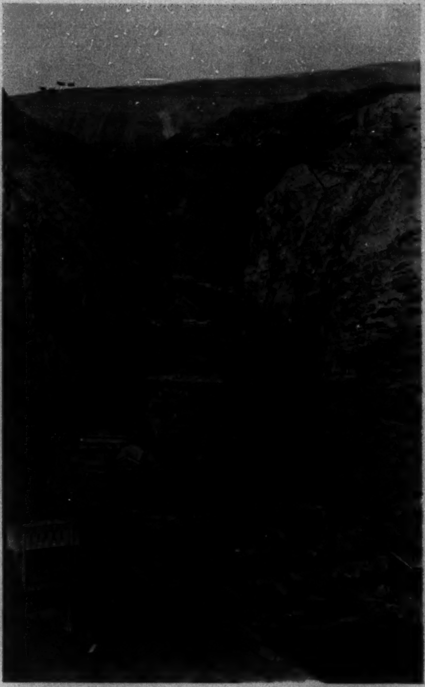
Another interconnection which is noteworthy in several respects is the 220-kv interconnection between Baltimore, Md., and Washington, D. C., placed in service early this year. It consists of a tap on the 220-kv single circuit from the Safe Harbor hydroelectric development to Baltimore. It has been justified primarily by storage power transactions; that is, it in effect creates additional generating capacity by the proper manipulation of the steam generation and hydroelectric storage. This interconnection of course, also, will serve for the purposes of emergency service and economy flow.

During the past 2 years, power system operators have been more largely concerned with improvements of operating technique and a careful combing over of possible economies that might be realized from existing interconnections.

### Frequency and Tie Line Load Control

One of the problems that has been receiving considerable attention, especially where several systems covering an extensive area with many power stations are involved, has been that of tie-line power-flow control with its related subjects of frequency and time control. The admirable papers of Sporn and Marquis, and of Purcell and Powell (see bibliography) exemplify the thought that has been given to this problem, and portray its status.

Elementally in a group of interconnected systems, where control of the tie line flow is necessary because of physical limitations or desired in order to meet contractual requirements, frequency (and time indication) must be regulated by some *one* system. Tie line flow is regulated by the other systems—each regulating the flow in only one designated tie line, usually in one of the lines with which it is directly connected—by variation of generator phase angle through governor control.


U. S Bureau of Reclamation Photo

**Boulder Dam, looking upstream through Black Canyon toward damsite, prior to beginning of excavation of middle gorge. The first concrete was poured early in June**

If 2 or more of the interconnections form a loop, the foregoing regulating scheme must be supplemented by a phase shifting device in one of the interconnections forming a part of that loop. The flow in one of the interconnections of that loop, usually although not necessarily the one in which the phase shifter is situated, must be controlled by the phase shifter.

In some groups of systems, manual operation under such a plan is satisfactory, especially where the controlled quantities are indicated on meters before the eyes of the respective operators controlling those quantities as against being relayed to them by telephone messages from distant points. In other interconnected groups, where conditions are not so favorable, the transient conditions caused by load variations and emergency conditions impose load swings on the frequency regulating station or on the tie lines, which exceed the limits of the equipment or are otherwise undesirable.

To the extent that these difficulties are caused by the limitations of manual control, automatic frequency control and tie-line load control devices have been developed and successfully applied. Where the difficulty has been the inability of the frequency regulating station to handle its task, effort has been directed toward distributing the frequency regulating function to several stations in different parts of the interconnected system. Automatic frequency regulators so distributed have been adjusted to operate successfully in parallel and, aside from distributing the frequency regulating burden, have eliminated erratic behavior of tie line flow. But where complete tie line control also is desired, they must be coördinated in their operation with tie-line load control devices. Development work on such coördination is in progress.

In the case of tie line control, whether it be manual or automatic, difficulties arise when the controlling station is remote from the controlled point; perhaps telemetering principles will be resorted to in such cases. A case in point is an interconnection in northern New Jersey between the systems of the Public Service Electric and Gas Company and the New Jersey Power and Light Company, the flow over which at times is being regulated by the Conowingo hydroelectric plant in Maryland some 130 miles away. Communication between the controlled and the controlling points is by telephone. The control, of course, is rather rough, but further refinements in this case are not warranted.

## PHASE SHIFTERS

The problem of power flow control in interconnection loops referred to previously will become of increasing importance if and when business conditions warrant the installation of additional interconnections between systems which at present are directly or indirectly interconnected.

Phase shifting by quadrature additions to voltage either in the interconnection transformers themselves or in separate series units is, of course, technically a very satisfactory solution. But such equipment adds considerably to the cost of an interconnection and may make it uneconomic. Consider the case of Company *A* which for several years has had a low voltage interconnection with Company *B;* Company *C*, which is interconnected with Company *A*, desires to establish a large, important, high voltage interconnection with Company *D*, which in turn is tied in with Company *B*. The loop thus formed renders some one of the original interconnections inoperative, unless phase shifting equipment be installed. Since the cost of phase shifting equipment is proportional to the size and voltage of the interconnection, the cost of installing such equipment in the new interconnection may be prohibitive; perhaps it may be installed less expensively in one of the older ties. If so, questions of ownership, financing, cost responsibility, and coöperative control become complicated.

In some cases it may be possible to omit phase shifters, if the resulting uncontrolled power flow is physically tolerable and if satisfactory contractual and billing arrangements among the companies involved can be made. Contractual difficulties usually are slight when only 2 companies are involved, but if there are 3 or more companies in the loop, such solutions are not always available.

Note should be made of the rather large phase shifting transformers in use by the Texas Power and Light Company at their Temple substation, as described in the *Electrical World*, November 22, 1930. Transformers of this type can be arranged to serve either as phase shifters or as voltage-ratio changers, which may be desirable as changes in contractual or corporate relationships occur. So far as known the largest phase shifter yet built will handle the output of a 100,000-kva 26/66-kv transformer bank on a feeder between the State Line and Calumet stations in Chicago, Ill.

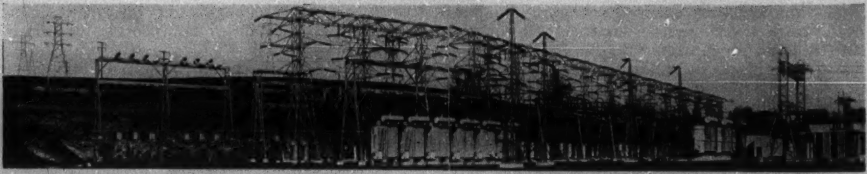
It is to be expected that if improved business conditions bring about additional interconnections, phase shifting devices will be required in more cases than in the past. Even where loops are not formed, the possibility of their occurring at a future time may call for designs which will permit the later installation of phase shifters.

## TIME REGULATION

Either by directed effort, or as a result of the installation of automatic equipment to facilitate power flow control, the time regulation of some systems has reached a point which is beyond practical requirements. The systems of the North Atlantic seaboard are operating with a time error not exceeding 20 sec. Another group of interconnected systems is said to be capable of operating with a frequency deviation not exceeding $^1/_{40}$ cycle (at 60 cycles) and a cumulative time error of not to exceed 3 sec.

## ECONOMY

The general search for savings in all branches of power system operation has not slighted any possibility for such savings arising from interconnection. There has been increasing appreciation of the behavior of power station production expense, particularly in the matter of distinguishing between those costs that are proportional to output and those that are not. The article on "Calculating Savings from Power Interchange" by E. C. Brown, appearing in the *Electrical World* of February 20, 1932, outlines in considerable detail the methods used in determining savings in the Connecticut Valley Power Exchange. P. B. Juhnke, in *Electrical World*, August 22, 1931, outlines perfections which have been made in the contractual relations of the companies operating in the Chicago district.



**Pleasant Valley (N. Y.) substation of the New York Power & Light Company, where the Niagara-Hudson and New York Edison transmission systems are interconnected through 2 banks of 110/132-kv 100,000-kva auto-transformers**

### NOMENCLATURE

As a result of discussion of the 1930 summer convention papers, the joint subcommittee on the subject of interconnection (formed by representatives of the committee on power generation and other interested committees) has formulated definitions of the various types of service rendered by interconnecting facilities. The joint subcommittee, however, has not yet taken steps toward their official adoption.

### INDUSTRIAL INTERCONNECTIONS

Exigencies of the time have occasioned considerable study of the principles of interconnection between utility systems and the power plants of industrial customers. Industries utilizing quantities of process steam or having available by-product fuel have shown continued interest in by-product power production by the installation of high pressure boilers with extraction turbine-generating apparatus. This development frequently results in the definite coöperation between industry and utility in the production of both steam and electric power. To the several notable instances mentioned in the 1931 report of the power generation committee should be added that of the Schenectady mercury-vapor-steam plant which is interconnected with the lines of the local utility. Principles involved in analyzing the services and economic results of such interconnections do not differ from those which apply to interconnections between power companies. However, in arriving at contractual arrangements with such industrial plants, the commercial policies of the power companies cannot be overlooked. There must be coördination between these arrangements and the rate schedules of the companies. The universality of rate schedules interferes with a full general application of inter-utility interconnection principles to dealings with customers. While many special arrangements have been entered into with industrials, they have been principally with the larger plants. It is felt that interconnection with the many smaller industrial plants must be approached more from the standpoint of introducing interconnection principles into rate schedule modifications and applying them generally, rather than by a multiplicity of special arrangements with the individual consumers.

## IV—Steam Plant Practice in the United States

General trends in steam power plant design during the last 2 years have been toward plant simplification, rehabilitation, and increased economy of operation, rather than to further elaboration in new or existing stations. Operating steam temperatures have continued to increase and several stations now use steam at 800 to 850 deg F. As now accepted, the upper limit of steam temperatures is 850 deg F, but experiments with steam at higher temperatures are being carried forward as, for example, at the Delray Station of the Detroit (Mich.) Edison Company.

There has been no tendency during the past 2 years toward the use of steam at higher pressures, but during this period several 1,200- to 1,400-lb plants have been in successful operation. Only minor improvements in the design and construction of equipment to operate at those pressures have been necessary. While the foregoing is the generally accepted maximum pressure range for power plant practice today, investigation of steam generation at higher pressures has proceeded actively. Experimental series drumless boilers for steam pressures up to 3,500 and 5,000 lb per sq in., respectively, are in their second year of operation at Purdue University and at the plant of a boiler manufacturer. Studies have been made of heat transfer, of the flow of water-steam mixtures, and of the heat content of steam at high pressures. Several manufacturers have constructed steam generators for pressures as high as 2,500 lb per sq in. and for temperatures up to 1,000 deg F, for producing relatively small quantities of steam to be used in testing instruments and fittings. Experience being gained in the construction and operation of this high pressure equipment may prepare the way for the next increase in commercial pressures.

The fact that plants have been and are being operated successfully at the higher pressures mentioned warrants the further consideration of such pressures for new plants and the rehabilitation of old plants from the standpoint of first cost, economy of operation, reliability, and lack of operating difficulties. Since it has been proved that equipment can be successfully constructed for temperatures of 850 deg F, a relatively high economy can be secured by the use of 650-lb pressure without reheat. This is due in part to the increased operating temperatures that are possible. The adoption of the mercury cycle in an existing plant is essentially similar to the superposition of a high pressure (1,300 lb) turbine upon a lower pressure turbine system.

The trend toward plant simplification is characterized by the unit assembly arrangement in which a turbine is served by a single boiler. With the availability factor of modern boiler units rapidly approaching that of turbine units, there is a definite trend toward the use of boilers of high capacity with accompanying reduction in boiler plant investment. It is now common practice to install only 2 boilers per turbine in large plants, the Charles R. Huntley Station No. 2 of the Buffalo General Electric Company being an example. Consideration also is being given to the one-boiler-per-turbine layout; such an arrangement is used in the Port Washington Station of The Milwaukee Electric Railway and Light Company. There are no size limitations to this arrangement, as it is now possible to build a boiler unit with a capacity equal to the demands of any turbine unit.

## Boilers

Boilers are now in successful service generating over 1 million lb of steam per hour per unit and it is possible, even feasible, to build units of 2 million lb of steam per hour each. The steam capacity of boilers per foot width of furnace has risen steadily until now units are under construction with capacities as high as 17,500 lb per hour per foot, and units of much greater capacities have been designed and proposed.

The single-pass sectional-header boiler, without economizer, air heater or induced draft fan, has made some progress in this country for low load factor plants, such as steam heating and reserve for hydroelectric plants, and for plants having good load factors where low cost fuels are used. Single-pass converging-header boilers are used with economizers and air heaters for stations that are to operate at a relatively high load factor where it is desired to keep the draft loss for the unit down to a minimum with maximum heat transfer.

Welded drums now are permitted by the A.S.M.E. Boiler Code, making possible great progress in the adoption of this construction which is an important step forward in boiler design. The individual states are rapidly accepting this construction. Exploration of welded seams by means of X rays and gamma rays has kept pace with other advances in the welding art. Welded seams in plates up to $4^3/_4$-in. thickness now can be explored by X rays, and up to 6 in. by gamma rays.

Accurate steam temperature control for all conditions of load and operation is now desirable in many cases, the cost of metals and constructions necessitated by prevailing high temperatures making it desirable to operate at the upper design limits at all times. A method of such control is by means of a desuperheater located preferably in the intermediate position between the upper and lower sections of the superheater. The use of intermediate desuperheaters has a further advantage in that the quantity of alloy superheater tubes usually necessary when higher temperatures are encountered is held to a minimum by reducing the temperature of the steam before, and not after, it reaches the superheater outlet. Another method of temperature control is the combination of a convection superheater located in the boiler passes with a radiant superheater placed on the walls of a furnace designed for a moderate heat-release rate per unit of furnace volume. Temperature control by a swinging baffle in the path of the furnace gases, causing these gases to sweep more or less superheater surface, also has found application.

It has been found increasingly important in many central station plants to reduce materially the quantity of moisture carried over by the steam, and to reduce the amount of solids passing through to the turbine in order to prevent trouble from the deposit of solids on the turbine blading. One of the means by which this is being accomplished is the use of a new steam scrubber installed in the boiler drum, which washes the outgoing steam with the incoming boiler feedwater. Thus the solids, which ordinarily would be carried over by the moisture in the steam, are washed out and any moisture remaining in the steam is cleaner and freer of solids.

## Firing Methods

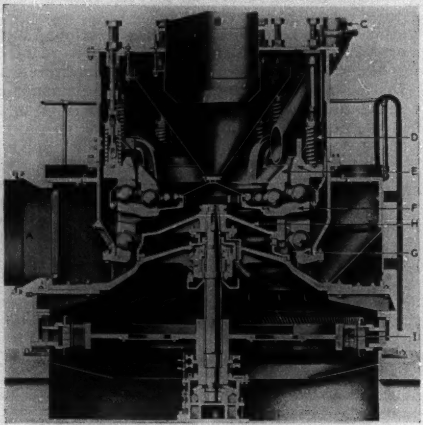
Methods of firing fuel have undergone no major developments during the past 2 years, although in many cases conversion has been made from pulverized coal firing, and in instances from stoker firing, to gas or oil firing. The completion of pipe lines from Texas and Oklahoma to Chicago has influenced the use of natural gas throughout the Mississippi Valley, in combination oil, coal, or gas burners.

Improvements in large stokers have been apparent in recent years. Developments in stoker fired equipment include the trend toward larger units and the increased use of zoned air-control. The latter method of operation results in higher combustion rates and steaming capacities of boilers. Tests on an experimental stoker installation under Philadelphia (Pa.) Electric Company's No. 8 boiler at Chester Station have indicated that a dry coal burning rate of about 72 lb per sq ft of projected grate area could be maintained for about 4 or 5 hr. This represented a fuel burning rate of 78 lb per sq ft, resulting from the return to the stoker of about 6 lb per sq ft of cinder collected at the back of the boiler. The tests indicated that continuous dry coal burning rates should be limited to about 60 lb per sq ft of projected grate area. Delray No. 3 of the Detroit (Mich.) Edison Company, also by use of zoned air-control has increased boiler efficiencies by 3 per cent on the average. Air zoning is accomplished by installing a number of individual wind boxes with adjustable damper-controlled entrance orifices under each retort. Air is in effect measured to each wind box, and the metering may be made the basis of automatic control.

Underfeed stokers are now available which with single-ended firing are capable of handling up to 18 million Btu per hour in high grade coal per foot width of furnace, and pulverized coal burners and furnaces now are being installed for single-ended firing as high as 25 million Btu per hour input per foot width of furnace.

The slag-tap furnace has proved to be important in permitting the most economic design of boiler unit, because of the high permissible rate of heat input per foot width of furnace and the lower setting height required. The slag-tap furnace is adapted especially to the use of low grade coals. There are now in excess of 60 slag-tap furnaces in operation in this country. Difficulties initially encountered with this type of furnace have been overcome by the use of water cooled furnace floors.

Difficulties with slag-tap furnace installations caused by the excessive slagging of boiler tubes with molten ash have resulted recently in the development of dust screen tubes to which studs are welded and covered with refractory material, for the purpose of presenting a surface to which ash dust would adhere and fuse to the point where it would drop off and thus maintain a stable surface. This construction is being applied also to furnace walls.



**Section of Babcock & Wilcox type B pulverizer installed at the Kips Bay station of the New York (N. Y.) Steam Corporation**

This mill pulverizes 50 tons per hour of 70 grindability coal from the Pittsburgh Seam to a fineness of 70 per cent through a 200 mesh screen and 98 per cent through a 40 mesh screen

A. Separating air inlet
B. Pulverized coal outlet
C. Coal inlet
D. Pressure regulating springs
E. Stationary rings
F. Rotating ring
G. Stationary ring
H. Driving yoke
I. Vertical synchronous motor

The universal, completely metal-cooled furnace in which solid, liquid, and gaseous fuels can be burned separately, or in combination, is being approached in several large central stations and allowed for in others. This design is made possible by the development of combination fuel burners for firing through water-cooled furnace walls; similar burners have been used also for vertical firing.

Progress has been made in both the direct fired and the storage system of pulverized fuel firing, each method having economic applications which can be determined best by a careful analysis of the conditions under which the plant is to operate.

The construction of a pulverizer with a capacity of over 50 tons of coal per hour installed in the Kips Bay Station of the New York (N. Y.) Steam Corporation was an outstanding development of the period. A unique driving mechanism is adapted to the 50-ton mill. No gearing is used, and the mill shaft is connected directly to the rotor of a 500-hp vertical synchronous motor at 72 rpm. The mill base rests directly on the stator frame. To overcome the difficulty of mill starting, especially when partly filled with coal, unusually high starting and pull-in torques were specified; overvoltage starting is used to obtain these.

### TURBINE-GENERATORS

The trend toward large capacity single-shaft turbine-generators noted in the last report apparently has continued in this country, although the number of machines purchased lately has been few. The 2-cylinder tandem-compound unit appears to be the preferred type at present for large capacities; a 150,000-kw 3-cylinder tandem-compound unit for 1,200-lb pressure and 825-deg F initial and resuperheat steam temperature was delivered in 1932. Five vertical cross-compound units are in operation in this country at 1,200-lb initial pressure.

Turbine operating experience during the past 2 years apparently has shown an increased degree of reliability which can be attributed definitely to improvement in the design of turbine details, and not to the lessened use of turbine-generators. There is concrete evidence that breakage of turbine blading because of vibration is being diminished. Other difficulties, however, are arising in consequence of: the use of higher steam pressures and temperatures; greater capacities requiring higher blade speeds; the desire to keep turbine and building investment to a minimum by using single-cylinder units of large-output; and in some cases, the necessity of operating units at reduced load. Troubles caused by these and other factors are: the erosion of turbine blading by moisture in the steam; deposits on turbine blading; difficulty in starting units after shutdown of a few hours; and oil fires.

While boiler water conditioning or control is usually desirable for all pressures, frequent turbine outages and reduction in turbine capacity because of blade deposits following the use of high steam pressure resulted in more emphasis on this phase of plant operation. The purpose is mainly for the reduction or elimination of scale-forming and corrosive substances from the water, and the maintenance of the proper sulphate to carbonate ratio to inhibit embrittlement of the boiler metal; although related is the prevention of foaming, priming, and carry-over, which results in deposits in superheater tubes and on turbine blading.

Tip speeds of turbine blading have been increased in recent instances to over 1,200 ft per second. Erosion of the blading by moisture in the steam increases with the speed of the blades, and now is recognized as a problem requiring solution. A comparatively large amount of moisture in the steam in the low pressure end of turbines seems to result from economic turbine design. Designs have been made for internal arrangements to drain the moisture from the turbine as it forms, but to date such efforts have been only partially successful. Higher initial steam temperatures are beneficial for the purpose, as well as reheating of the steam during expansion through the turbine. In all cases in this country except 6 turbines, reheating has been carried out with the use of either tandem- or cross-compound arrangement of turbine cylinders. Turbine manufacturers are making intensive studies of the resistance of blade materials to erosion and corrosion. Plating and coating of blades, and the attachment of strips of erosion resisting materials such as stellite to the wearing edge of the blade, have been tried. Laboratory tests with steam and water jets have indicated promising characteristics for steels which were surface-hardened by nitriding. Single turbines having blades protected by about 30 different methods and materials now are being operated to compare the endurance of the blades under actual operating conditions.

The use of higher steam temperatures, reduced internal clearances of turbines, turbine cylinders of larger capacity, and the necessity of frequent stopping and starting have resulted in difficulty in the starting of turbines after short idle periods. Uuequal temperature distribution throughout the turbine following shutdown has caused sufficient deformation of the turbine spindle and eccentricity of its axis to produce vibration if started in this condition. The use of a turning gear in conjunction with high pressure oil for floating the turbine shaft in its bearings has been of service in this connection; this practice has substantially reduced the time necessary to bring units to full speed, and has aided in maintaining close internal clearances and thus improving steam economy.

Another development along the same line has been that of turbine supervisory instruments for remote indication of turbine performance. These instruments will be useful also for outdoor generating equipment. The instruments will indicate or record turbine speed, shaft eccentricity, movement of parts as the result of temperature changes, vibration, and noise intensity resulting from improper contact of parts.

Recent oil fires in turbine plants using high temperature steam have stressed the necessity for better safeguards against this type of damage. Separation of the oil systems employed for lubrication and governing has been proposed, also the use of non-inflammable liquids. Redesign of the lubricating and governing systems also is being considered with the view of strengthening structural details and of preventing the access of oil to regions of high temperature in the event of casualties.

Welding has found increasing application in plant design in addition to the fabrication of boiler drums mentioned previously. High-pressure high-temperature steam lines are being welded and stress relieved in place. Many turbine parts now are being fabricated by the welding of plates and shapes, with the elimination of castings. The development of X ray testing for shop processes has helped the introduction of welding in the field of turbine manufacture.

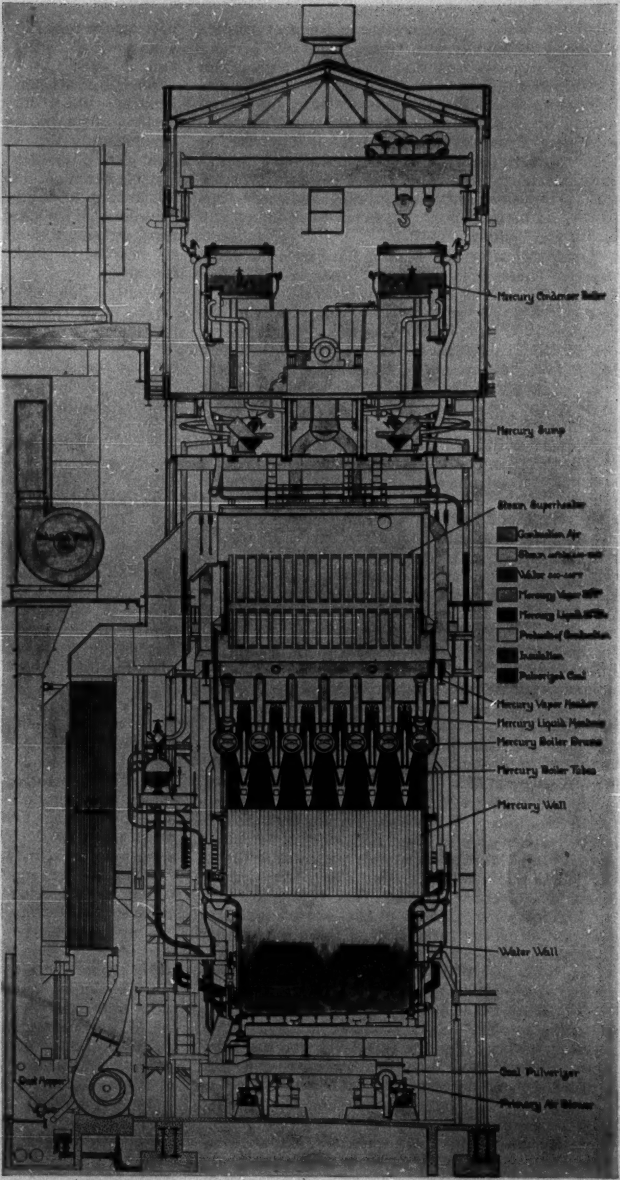
Condenser development has continued along the lines followed for several years, although the trend as to reduction in condenser surface per unit of turbine capacity has about stopped. The largest condenser of welded construction, 65,000 sq ft, recently was installed in the Kearny Plant of the Public Service (N. J.) Electric and Gas Company. The trend in favor of single-pass condensers of large size has continued; the largest condensers of this design were installed in the Hudson Avenue Plant of the Brooklyn Edison Company, where turbines of 160,000-kw capacity exhaust into single-pass condensers of 101,000 sq ft each. Tubes with an active length of 30 ft are used in these condensers, which is the longest installed to date. Rolling of tubes in both tube sheets is being adopted more widely, with resultant benefit throughout the steam and feed water cycle. Chlorination of condenser water for inhibiting sliming and algae growth in condenser tubes has been developed to a practical basis, and maintains condenser tubes in a greater state of cleanliness over longer periods resulting in increased turbine availability, reduced manual cleaning of tubes, and increased turbine economy.

Since the 1931 report of this committee there has been an increase in this country in the capacity rating of turbine-generators with a speed of 3,600 rpm. Single-cylinder partial-expansion or back-pressure units now are in service having ratings up to 18,000 kw. Tandem-compound units of 15,000-kw rating are in use; these expand to normal condenser pressure. Tandem-compound machines of 25,000-kw capacity are under construction.

Generator purchases during the past 2 years have been too few to warrant additional conclusions, beyond those noted in the last report, about the use of higher generator voltages. It appears though that increased attention is being given to the subject of the most economic generating voltage; the advisability of holding to established voltages is being questioned, particularly where generators are connected directly through transformers to the transmission system. The development of a 36-kv 31,250-kva turbine-generator for installation in the Langerbrugge power plant in Belgium records an increased generating voltage in European practice over the 33-kv generators installed in 1929 in the Brimsdown Plant, England. Considerable study has been given to the problem of protecting generators connected directly to overhead lines against voltage surges. The increased knowledge of the nature and magnitude of surges and reflections obtained by the use of the cathode ray oscillograph has made it possible to apply protection by means of suitable lightning arresters and capacitors with some degree of assurance.

### DEVELOPMENTAL WORK

Diphenyl compounds, which have been in considerable use as heat-transfer mediums in the chemical industry, were adopted for air preheating at the Bremo Bluff Station of the Virginia Public Service Company, because the extreme height of the units makes the flue gas outlet and source of heat for air preheating remote. The diphenyl compound is circulated between a heat absorbing element in the path of the flue gases and a heat releasing section in the air ducts of the furnace and mills. The relatively small dimensions of this equipment compared with the usual air preheater and duct work, resulted in a decrease in building height and volume. Reduced draft-fan power and radiation loss also were reported.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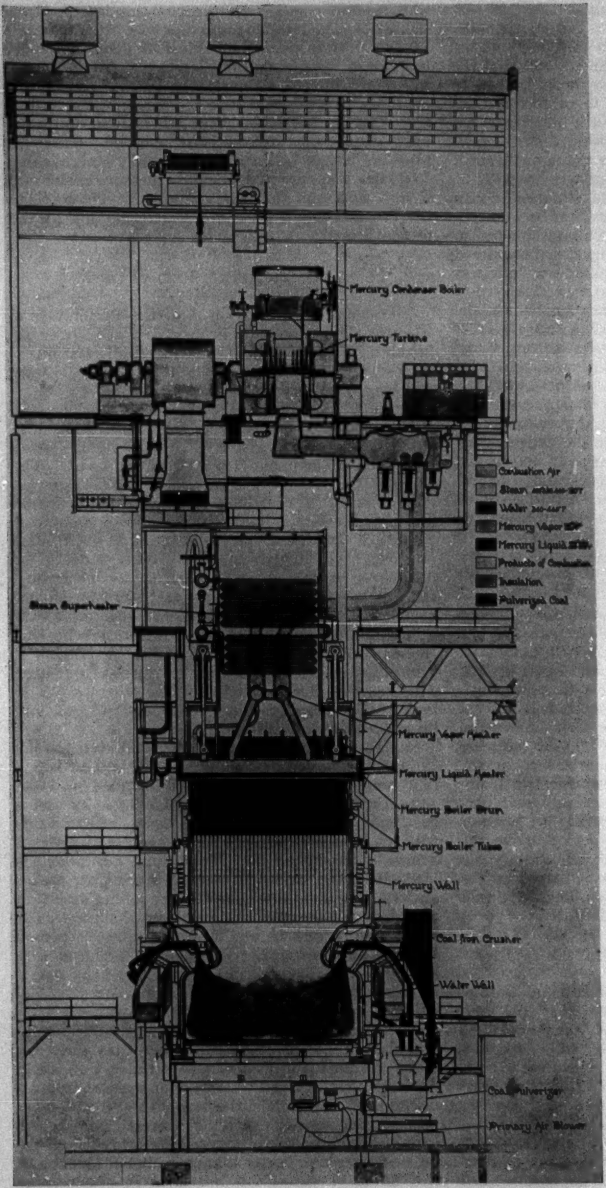
Mercury Sump
Steam Superheater
Combustion Air
Steam
Water
Mercury Vapor
Mercury Liquid
Products of Combustion
Insulation
Pulverized Coal
Mercury Vapor Header
Mercury Liquid Header
Mercury Boiler Drums
Mercury Boiler Tubes
Mercury Wall
Water Wall
Coal Pulverizer
Primary Air Blower
Coal Hopper

Vertical section of the General Electric mercury-steam equipment installed at the Kearny station of the Public Service (N. J.) Electric & Gas Company


Mercury Condenser Boiler
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Mercury Vapor Header
Mercury Liquid Header
Mercury Boiler Drum
Mercury Boiler Tubes
Mercury Wall
Coal from Crusher
Water Wall
Coal Pulverizer
Primary Air Blower

**Vertical section of the General Electric mercury-steam equipment installed at the Kearny station of the Public Service (N. J.) Electric & Gas Company**

Improvement of methods for the removal of fly ash from stack gases has continued. After several years of development of an improved scrubbing process in the Kneeland Street Plant of the Edison Electric Illuminating Company of Boston, Mass., 95 per cent of the fly ash from the combustion of pulverized coal now can be removed. Experimental work is progressing steadily and it is expected that the effectiveness of the process will be improved further. At the Michigan City Station of the Northern Indiana Public Service Company an electrical precipitator of somewhat larger than normal size with correspondingly low gas velocities has given apparent efficiencies of dust removal ranging from 92.3 to 98.4 per cent.

A steam turbine in the Delray No. 3 Plant of the Detroit Edison Company has been operating with 1,000-deg F steam for a large portion of the time since the latter part of 1931. The installation consists of a 10,000-kw turbine with the generator terminals connected to the main station bus and operating under normal production conditions. Steam for the unit is generated in the main station boilers at 400 lb and 700 deg F, is raised to 1,000 deg F in a separate oil fired superheater and arrives at the turbine throttle at 365-lb pressure. Turbine troubles due to such high temperature operation have been few and the high temperature equipment has good operating records; final conclusions about the installation, however, depend upon further experience.

The mercury-vapor-steam-electric power plant nearing completion at Schenectady, N. Y., represents an attempt out of the ordinary to eliminate all unnecessary expense in building construction. Static apparatus such as evaporators, deaerator, mercury-steam condenser-boilers, air preheaters, etc., have been placed out of doors as well as the 20,000-kw mercury turbine and the 6,000-kw pressure-reducing steam turbine. The steam boiler and the mercury boiler have been sheltered in glass as well as office space in the basement and coal unloading facilities; the latter have been housed to facilitate thawing in winter and to protect the adjacent factory from coal dust. Such housing as has been provided consists of factory-welded steel panels glazed in a manner quite as simple as the metal sheet lagging provided for apparatus regularly housed.

The mercury-vapor equipment in the South Meadow Station at Hartford, Conn., has been in continuous operation since changes were completed in 1932. The furnace now burns oil instead of powdered coal; steam is generated in the condenser boilers at the design pressure of 425 lb per sq in. and is used in the high pressure steam section of the station. For the 5-month period between June 1 and November 1, 1932, when sufficient load was available to load the mercury turbine fully, a total of 73,330,000 kwhr was generated at a heat rate less than 10,000 Btu per net kwhr; the load factor during that period was 87 per cent.

Since 1931 there have been mercury-vapor power installations of 20,000 kw each at the Schenectady Works of the General Electric Company and at the Kearny Station of the Public Service (N. J.) Electric and Gas Company. In each case operating conditions for the mercury turbines are as follows:

| | |
|---|---|
| Initial pressure | 125 lb per sq in. gage |
| Initial temperature | 958 deg F |
| Exhaust pressure | 3 in. mercury, absolute |
| Exhaust temperature | 485 deg F |

Steam generated in the condenser-boilers at both installations amounts to 325,000 lb per hr. At Kearny the steam is generated at 365 lb per sq in. gage and 750 deg F initial temperature, which is sufficient to generate 33,000 kw in a steam turbine. At Schenectady the steam is generated at 400 lb, 760 deg F initial temperature, is reduced in pressure to 200 lb by passing through a 6,000-kw reducing turbine and thereafter finds industrial use in the Schenectady Works of the General Electric Company. In each case the furnace is provided partially with mercury walls and partially with water walls. At Kearny the turbine is placed above the boiler as at Hartford so as to provide gravity return. At Schenectady the turbine is placed on the floor as in an ordinary power station, and the liquid mercury is pumped back to the boiler.

## Operating Results

Despite the lack of new equipment and the decrease in power generation, the average coal consumption in the United States has fallen from 1.62 lb per kwhr in 1930 to 1.51 in 1932. This decrease may be accredited to the resultant gains from experimentation in higher steam temperatures and pressures; refinements in operating procedure; greater reliance on generating equipment and consequent reduction of number of units in service; high load factors on those operating; and the greater relative use of the more economical units. The trend toward unit assembly also is an effect of this increased reliability. The notable minimum heat rates achieved by the stations listed in Table I of the 1931 report have been maintained and lowered a per cent or 2 in certain instances during the past 2 years; but on the whole the heat rate of representative power plants has reached the point where little improvement can be expected without some major innovation in design. Steam temperatures approaching 1,000 deg F apparently promise a measure of thermal saving, although the mercury vapor cycle presents the greatest opportunity for heat reduction at the present time.

## Plants Exemplifying Recent Designs

The evolution of Station A of the Pacific Gas & Electric Company, San Francisco, Calif., from its beginning in 1901 to the present rebuilt station, is interesting. The completed station of 260,000 kw will occupy no more space than the 18,000-kw equipment of 1905. During 1931, 2 50,000-kw vertical-compound turbine-generators began operation, and subsequent economies have resulted in overall station heat rates of less than 12,000 Btu per kwhr. The new boiler plant comprises 3 500,000-lb per hr cross-drum boilers, 2 of which have reheaters. Steam leaves the boilers at 1,400 lb per sq in. pressure and 750 deg F, and 350 lb per sq in. and 750 deg F after reheating. The high pressure unit running at 3,600 rpm is connected to a 12,500-kw generator; the low pressure unit running at 1,800 rpm is connected to a 37,500-kw generator with a 250-kw exciter on the same shaft. A feature of the reheating element is a steam reheater using saturated steam at 1,400-lb pressure in series with a flue-gas reheater. This has the effect of flattening the reheat curve at low ratings. Boiler firing is by natural gas and burners can use oil as standby fuel.

Hudson Avenue Station of the Brooklyn Edison Company enlarged its capacity by 320,000 kw which represents the major equipment installed in 1932. This plant now has a capacity of 770,000 kw and is the largest power station in the world. Eight bent-tube multi-drum boilers, with separate dry-steam drums, were installed. The output per boiler is 530,000 lb of steam per hour at 400 lb per sq in. and 750 deg F. A leading feature in the design of the boilers is the underfeed stokers which are 26 ft wide, with 15 retorts, and 26 ft 8 in. long, exceeding by 3 ft any stoker previously built. The stokers and also the clinker grinders are driven by a hydraulic variable speed transmission; low installation cost made this type of drive advantageous over electrical systems. Two 160,000-kw tandem-compound units were installed. These turbines run at 1,800 rpm with initial steam conditions of 400 lb per sq in. and 730 deg F. The high pressure cylinder contains 15 stages and the low pressure, 4 double-flow stages. Steam extraction for feed heating occurs at 2 high pressure stages. Performance on the units is 1 per cent better than guaranteed; and since the 320,000-kw addition has been in service, the over-all station heat rate has fallen from 15,500 Btu per net kwhr approximately to 13,320.

Bremo Bluff Station of the Virginia Public Service Company has several features indicative of recent trends. The steam generating equipment consists of 2 inclined-tube single-pass boilers, each rated at 200,000 lb per hr evaporation and fired by pulverized coal. The diphenyl compound air-preheating system is used. The unit assembly idea is followed, each boiler serving a 15,000-kw tandem-compound condensing turbine designed for 450-lb pressure and 825 deg F. Steam is bled from 4 stages to rain-type feed water heaters. The units operate at 3,600 rpm. Another feature of the station is its centralized control room midway between the boiler and turbine rooms. Both turbine and control panels are in this room and enable one operator to control a large number of circuits.

Burlington Station of the Public Service (N. J.) Electric & Gas Company is an outstanding example of economies obtained by rehabilitation. An 18,000-3,600-rpm turbine-generator operating at 650 lb per sq in. steam pressure and 850 deg F total temperature is superposed on 3 older units, each of 12,500-kw capacity operating at 190 lb per sq in. and 150 deg F superheat. Thus the machines now form a 55,500-kw 4-cylinder compound unit that has reduced the station heat rate by 37.5 per cent (from 24,000 to 15,000 Btu per kwhr). The new machine is the largest capacity unit at this speed in existence.

## V—Oil and Gas Power

Several progressive features are evidenced in the Diesel engine field, such as reduction in weight, use of trunk pistons of large diameter, and increased speed. The increased use of alloy steels is noticeable, also the discontinuance of air injection in favor of mechanical injection. The trend in small plants is largely to the use of the single-acting 2-cycle engine.

The City of Vernon (Calif.) Power Plant will contain 5 7,000-hp double-acting 2-cycle engines and will form the world's largest Diesel-electric power plant. Each engine has 8 cylinders 24 in. by 36 in., runs at 167 rpm, and will drive a 5,000-kw generator.

The Lamoka (N. Y.) combination gas-electric hydroelectric and pumped-storage plant of the Lamoka Power Corporation is unique. The installation consists of a 2,000-hp vertical-shaft hydraulic turbine in operation, and a 7,500-hp turbine under construction. The turbines operate under a net head of 385 ft. One vertical 1,200-hp 6-cylinder 4-cycle gas engine drives an 800-kw a-c generator, and each of 3 1,800-hp engines drives a 1,250-kw generator. Each 1,800-hp unit consists of 2 6-cylinder engines with the generator and flywheel between. These engines are the largest of their kind in this country. During off-peak periods, the gas engine driven generators supply power to pump water into the hydro-plant reservoir by means of one 8,000-gpm and 2 16,000-gpm motor-driven pumps. Natural gas is brought from wells 1,750 ft under the land owned by the power company; it is probable that this is the only combination gas and water power plant using these 2 resources from the same land.

## VI—Foreign Steam Plant Developments

There have been no pronounced developments in power generation abroad since 1931, with the exception of the building of the "grid" scheme of transmission in Great Britain. This ideal scheme calls for a few new large, efficient power plants at favorable locations feeding into some 3,000 miles of transmission system, tying all plants together. All load dispatching will be done at a central point in London. The transmission voltage is either 132, 66, or 33 kv. Substations will tap the transmission grid to supply communities with power. The plan requires the abandonment of many small and inefficient plants.

Present English practice seems to favor use of steam at 600 lb and about 850 deg F. In Europe, pressures range from the moderate up to the critical pressure of 3,200 lb, which has been employed in one unit at Langerbrugge, with several installations between 1,200 and 1,800 lb. With few exceptions 850 deg F is the limiting temperature.

The report of the Electricity Commission of Great Britain last year shows several installations having a thermal efficiency of from 22 to 24 per cent obtained with moderate pressures not exceeding 650 lb, and fairly high temperatures. These efficiencies are all being obtained with English coal having a considerably lower Btu value than the coal generally used in the United States.

There has been a decided trend toward the use of larger turbine units, capacities ranging up to 100,000 kw with 50,000 kw appearing to be the popular size. Manufacturers are prepared to build 3,000-rpm 50-cycle machines in the larger sizes, and there is one unit of 80,000-kva capacity built for this speed.

The use of larger boiler units increases, and many units are in operation with a steaming capacity of from 200,000 to 300,000 lb per hour. Although furnace sizes also have been stepped up, they still average a little smaller per unit of boiler capacity than those of the latest American practice. The use of water walls is increasing.

Practice in fuel burning equipment shows a tendency to favor stokers over powdered fuel. The forced-draft chain-grate stoker is very popular in England probably because the quality of the fuel used is quite favorable to the use of the chain grate. The change in trend from powdered coal to stokers seems to be explained by 2 reasons: the lower initial cost of the stoker, and the lesser difficulty in taking care of the kind of dirt in the flue gases from the stokers.

Fly ash removal has been given much attention. An enormous amount of work has been done in developing centrifugal and wet types of eliminators and electrostatic precipitators. German engineers seem to favor the latter type, while in England many stoker fired plants are getting good results with centrifugal and dry type separators. This is much more important abroad than it is in the United States because the average ash content of the fuel is much greater.

English practice favors the straight tube boiler although the bent tube Stirling boiler also is used. In Europe, however, the proportion of bent tube boilers is much larger and they are of a wide variety. Several interesting and radical designs of boilers have been developed which are in commercial operation. The urge for this development work apparently is a desire to use much higher steam pressure without materially increasing the cost of the boiler unit.

**Ariel dam and power house of the Inland Power & Light Company on the Lewis River, Wash. This plant is said to contain the largest overhung generator with revolving field installed to date; it is rated 56,200 kva, 120 rpm**

The use of heat accumulators such as the installation in Charlottenburg, Germany, apparently has made little progress. While this installation successfully handles peaks of certain duration, apparently the initial cost, space required, and low efficiency are factors that are retarding this development.

There is nothing especially new in the switch house. The general practice in England, largely because of the Board of Trade Rules, is the use of "iron-clad" switchgear placed indoors. European practice is similar to American. With few exceptions, no foreign switch house has to handle as large quantities of energy as do many American stations.

## VII—Developments in Hydroelectric Practice

Progress in hydroelectric practice during the past 2 years was foretold to a large extent in the 1931 report of this committee, when the impending developments in the use of the Kaplan turbine in this country were discussed. Other than this significant step there does not appear to be any distinctive innovations of major importance in the designs of the hydroelectric projects placed in operation during the past 2 years. The probable future trend, if any, with regard to the type of propeller turbine that may be preferred for low head plants, however, is not yet clear. The Kaplan, or automatically adjusted-blade turbine, was installed in the Safe Harbor Plant on the Susquehanna River in Pennsylvania; manually adjusted-blade turbines in the Rock Island Plant on the Columbia River in Washington; and fixed-blade turbines in the Chats Falls Plant on the Ottawa River in Canada. These plants are typical examples of the most recent use of propeller turbines for low head developments. A very interesting high head development was placed in service on the Mokelumne River in California. The Ariel Plant on the Lewis River, Washington, and the Wyman Dam development on the Kennebec River, Maine, were representative of medium head designs and displayed novel ideas in building and superstructure designs.

Interest in cavitation investigations in this country has continued largely as the result of the increasing use of the propeller turbine in low head plants. The first cavitation research laboratory in the United States was recently opened at the Massachusetts Institute of Technology, Cambridge, and there are now several commercial and institutional laboratories equipped for making cavitation tests on model runners. Testing of models of all important structures comprising a hydroelectric development is now accepted practice, and is well exemplified by the extensive model studies made for the Boulder Dam on the Colorado River. The European practice of using multiple current meters distributed over the intake area for the field testing of hydraulic turbines, was introduced in the United States at the Safe Harbor plant, where the short length of intake passage was believed to render the commonly used methods of water measurement of doubtful value.

The number of pumped storage developments on this continent is small compared with those in Europe, but the possibility of regenerative pumping at the Safe Harbor plant by means of the dual use of the same unit as a turbine and a pump has been investigated recently. Turbine manufacturers have developed runners suitable for such dual use, and the electrical problems incident to reverse operation at either a similar speed or a dual speed appear possible of ready solution. The limited practice heretofore in this country has been to install a motor driven pump entirely separate from the turbine-generator, although both pump and turbine are connected to the same penstock. The arrangement commonly found in Europe consists of a single electrical element used either as a generator or motor, with a permanently connected turbine on one side and a clutch connected pump on the other.

Discussion of the economics of hydroelectric projects during the past 2 years has been focused on: the determination of the cost characteristics of different types of developments; the relative economy of water power as compared with steam power; the influence that the incremental cost of hydroelectric capacity has upon the size of development; and the peak substitutional value of water power as compared with steam power on the available load curve. The latter 2 factors are of particular importance in the consideration of pumped storage and regenerative installations.

Development of the Mokelumne River in California having a drainage area of 365 square miles, over a gross static head of 5,100 ft by means of 4 plants in series on the flow line without appreciable intervening storage, may be the last high head development for some time on the Pacific Coast. The maximum flow used, 650 cfs, is 80 per cent of the average yearly stream flow, which is regulated almost completely by storage reservoirs having a volumetric capacity equal to $^{1}/_{3}$ of the volume of run-off. There are 3 impulse installations operating at gross heads of 2,089, 1,265, and 1,219 ft; and 2 Francis wheel installations for heads of 285 and 245 ft. One of the 5 main dams is the largest rock-fill dam in the world, having a height of 328 ft and a crest length of 1,300 ft. The peak capacity of the plant is 144,000 kw and will be used about 80 per cent of the time.

Tiger Creek plant of the Pacific Gas & Electric Company on the Mokelumne River, Calif. This plant contains 2 double overhung impulse units operating on a head of 1,190 ft and driving 2 generators each rated 30,000 kva

The Rock Island plant on the Columbia River is the first major low-head run-of-river development on the Pacific Coast and also the first step in the development of the hydroelectric possibilities of the Columbia River. The drainage area above the plant is 90,000 square miles; maximum and minimum recorded flows have been 740,000 and 21,000 cfs, respectively, and the mean flow is 121,000 cfs. The head for the initial installation of 4 21,000-hp units is 32 ft; it will be increased to 48 ft with the addition of more units, of which there ultimately will be 12. Initial full draft water requirements are about 75 per cent of the minimum steady flow, and about 135 per cent of the lowest recorded flow. Because of the low- and varying-head conditions, manually-adjusted-blade propeller wheels were installed; these have a diameter of 223 in. and are the largest propeller wheels on this continent. The plant operates at a capacity use factor of about 90 per cent, which, in comparison with the run-of-river plants in the eastern section of the United States, represents a relatively small capacity installation with respect to the minimum flow capacity.

The Chats Falls plant on the Ottawa River, Canada, is a low head development 53 ft, showing a somewhat greater ratio of installed capacity to regulated flow capacity. The drainage area above the plant is 34,000 square miles, but because of the presence of numerous lakes the minimum dependable flow is now 22,000 cfs. The 8 28,000-hp fixed-blade propeller units require a full draft equal to 2 times the minimum flow. This plant serves a large system that derives its entire supply of electric power from hydroelectric sources.

The Safe Harbor plant on the Susquehanna River is notable for having the highest powered propeller turbines in the world, the units being rated at 42,500 hp under a head of 55 ft. The full draft requirement of the plant initially is about 12 times the minimum regulated flow; the yearly use factor will approximate 50 per cent. The initial installation consists of 6 units, with head-works structures for 6 additional units. The hydraulic and electrical design anticipates the dual use of the units for generation and regenerative pumping; the plant will be the first low head development planned for such operation, which is readily accomplished because the Safe Harbor plant discharges directly into the pond formed by the Holtwood dam 8 miles farther down the river. The electrical layout in the plant provides for: 3-phase 60-cycle, and single-phase 25-cycle generation; 60-cycle low voltage busses; and control of transformers placed above the bus galleries for stepping up to 69 and 230 kv for transmission. The 25-cycle generators will be the largest single phase waterwheel units in the country, having a rating of 37,500 kva at 80 per cent power factor. High voltage switch yards for the control of outgoing 60- and 25-cycle transmission lines will be placed on shore adjacent to the power house. Outdoor frequency changers rated at 25,000 kw, 80 per cent power factor, will be installed below the bulkhead connecting the power house with the shore.

The Ariel and Wyman Dam plants exhibit an interesting treatment of superstructure design, which in both plants consists of a low roof with removable hatches over the generators. Outdoor 2-leg gantry cranes serve the generator areas; that at the Ariel plant is the largest outdoor power house crane yet built, having a span of 67 ft, a lift of 80 ft above crane rails, and a capacity of 350 tons. The Ariel plant is notable also for having the largest overhung generator with revolving field installed to date; it is rated 56,250 kva at 80 per cent power factor, 120 rpm. Other novel features of the Ariel plant are the location of a part of the power house upon a concrete arch spanning a deep gut in the foundation rock, and the location of the control room in an adjacent but separate building. The drainage area above the Ariel plant is 733 square miles. One 55,000-hp 170-ft-head unit has been installed initially; the complete plant will contain 4 units with the expectation of using seasonal storage for low use-factor operation. The Wyman Dam plant has an initial installation of two 34,000-hp 135-ft-head units, with provision for a third unit in the future. The use factor of this plant will be of the order of 45 per cent.

Records for maximum size and extreme conditions of installation of propeller turbines continue to remain with European plants. Among the more notable are the following Kaplan installations:

| Plant | Horsepower | Head, Ft | Runner Diam, In. | Discharge, Cfs | Speed, Rpm |
|---|---|---|---|---|---|
| Vargon, Sweden | 15,000 | 14 | 315 | 11,090 | 46.9 |
| Swir, Russia | 37,500 | 36.1 | 292 | 10,240 | 75 |
| Shannon, Ireland | 33,000 | 106* | 161 | 3,040 | 167 |

* Head initially is 82.25 ft.

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*Fuels and steam power division.

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†Hydraulic division.

# Power Transmission and Distribution

## ANNUAL REPORT OF THE COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

IN SPITE OF business conditions, power transmission and distribution activities have been maintained during the past year. Much of the work of the power transmission and distribution committee has been divided among and carried on by several subcommittees. Activities of these subcommittees during the past year are summarized briefly in this report.

### Steel Transmission Towers and Conductors

The work of this subcommittee has been subdivided into 3 groups covering: (1) steel towers, (2) Clearances and Electrical Characteristics, and (3) Conductors. The following items are under consideration.

1. Hinged and rigid crossarms.
2. Straight line compression formula for columns.
3. Fatigue indications at clamps.
4. Rotated towers.
5. Recommended form for service records.
6. Clearances as affected by heating of conductors.
7. Vibration of transmission conductors.

This subcommittee has been in touch with the investigation of embrittlement of hot dipped galvanized steel, which has been covered by a report to be found in the *Proceedings* of the American Society for Testing Materials, v. 32, Part II, 1932. Study is now being given to prestretching of A.C.S.R. cables. A report entitled "Modern Steel Tower Transmission Lines" was published in Electrical Engineering for April 1933, p. 243.

### Distribution

The subcommittee on distribution has been working intensively on the preparation of a coördinated group of papers for a session at the 1934 winter convention. It is proposed that this program will cover certain phases of the economics of electric power distribution based upon actual areas in the districts of several operating power companies.

### Cable Developments

The amount of new cable construction work during the past year has been rather limited. There have been no electrical failures on any of the 132-kv oil filled cable lines operating in New York City and Chicago, Ill. The experimental 132-kv lines in Chicago and Newark, N. J., have continued without incident for another year, except for one joint failure in Chicago. Additional 35-kv oil filled cables have been installed in Los Angeles, Calif.

The 2 outstanding high voltage submarine cable installations operating at 69-kv have continued in successful operation: one across the Delaware River, near Wilmington, Del., of the "solid" type, for $3^1/_2$ yrs; the other across the Columbia River, near Portland, Ore., of the oil filled type, for about 1 year.

Two unusual submarine cable installations have been made during the year. The first is across the East River, New York City, consisting of 14 cables each, 2,330 ft long, laid 2 at a time by a novel method of installation in a narrow trench, part blasted out of solid rock. Half of the cables are of the oil filled type and half are of the "solid" type. The other installation consists of 15 cables, installed 5 at a time, from the Hudson Avenue Station, Brooklyn, N. Y., across Wallabout Bay, each 3,300 ft long without joints, the cables all being of the "solid" type. Both installations consist of 3-conductor, 500,000-cir mil paper-insulated 27.6-kv cables.

A recent installation of single-conductor 69-kv paper-insulated cable involves conductors 2,100,000 cir mils in cross section; the skin effect was reduced by making the conductor out of several sectors of stranded conductor, the sectors being lightly insulated from each other. The conductor is wrapped with copper tape to give a smooth electrical surface.

There has been considerable activity in the development of cable without lead sheath for medium and low voltage distribution; this cable may be buried directly in the ground, or pulled into ducts.

### Interconnection and Stability Factors

This subcommittee has been relatively inactive during the year because the joint interconnection subcommittee, with which it was to coöperate, was not organized, the parent technical committees finding such organization unnecessary at this time.

### Standardization

Standardization activities in the transmission and distribution field have been proceeding at a modest pace. National existing standards and national standardizing projects under way or to be initiated are, in common with other electrical standards, being brought under the jurisdiction of the new Electrical Standards Committee. This committee has been organized to coördinate all standardization of a national character in the electrical field. The following is a brief résumé of the more important recent standardization activities in connection with transmission and distribution:

1. Parts I and II of the "Code for Protection Against Lightning" which is now an American standard, have been revised by the sectional committee, these revisions are in process of approval by the American Standards Association.

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*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION: P. H. Chase, *chairman;* R. N. Conwell, *vice-chairman;* T. A. Worcester, *secretary;* F. E. Andrews, G. M. Armbrust, H. W. Bibber, D. K. Blake, E. S. Bundy, A. B. Campbell, C. V. Christie, W. A. Curry, O. G .C. Dahl, A. E. Davison, R. D. Evans, F. M. Farmer, C. L. Fortescue, T. H. Haines, Edwin Hansson, C. F. Harding, K. A. Hawley, L. F. Hickernell, C. R. Higson, J. P. Jollyman, A. H. Lawton, H. L. Melvin, J. S. Parsons, F. W. Peek, Jr., L. L. Perry, D. W. Roper, H. J. Scholz, H. R. Searing, A. E. Silver, D. M. Simmons, C. T. Sinclair, L. G. Smith, H. H. Spencer, Philip Sporn, W. K. Vanderpoel, and H. S. Warren.

2. The American Society for Testing Materials has issued "Tentative Specifications for Insulated Wire and Cable: Performance Rubber Compound."

3. Three preferred types of impulse test waves, namely, 1x5, 1x10 and $1^{1}/_{2}$x40$\mu$ sec have been recommended by the lightning and insulator subcommittee of the power transmission and distribution committee for testing insulators. One of these standard waves, $1^{1}/_{2}$x40$\mu$ sec, has been recommended by the transformer subcommittee of the A.I.E.E. electric machinery committee for testing transformers.

4. An A.S.A. sectional committee on power switchgear has been organized, and hereafter the various revisions of the A.I.E.E. standards on switching apparatus will be made through that committee. A joint N.E.L.A.-N.E.M.A.-A.E.I.C. committee on oil circuit breakers was set up to crystallize views with reference to standardization of dimensions, duty cycles, ratings, etc.

5. Specifications for weatherproof and for heat resisting wires and cables, and for impregnated paper insulation for wires and cables recently have been approved as American standards. The A.S.A. sectional committee which has these and other standards in charge, has several other wire and cable specifications in various stages of development.

6. Proposed American standard definitions of electrical terms including a comprehensive list of transmission and distribution terms have been published by the A.I.E.E. as a progress report.

### LIGHTNING AND INSULATORS

Considerable progress has been made during the past year in placing impulse testing of insulators on a common basis. The 3 preferred test waves recommended by lightning and insulator subcommittee last year have been accepted generally as a basis for comparative tests of impulse strength of insulators, although in some laboratories, where difficulty was encountered in producing the $^{1}/_{2}$x5-$\mu$ sec wave, a 1x5-$\mu$ sec wave has been used with fairly comparable results where flashover takes place on the tail of the wave.

In addition to agreeing upon and using defined test waves in impulse testing of insulators, an important phase of the problem is the laboratory technique in making tests. Considerable study has been given this subject, and definite progress has been made.

Field research of lightning on actual electric lines has been continued on a much restricted basis this past year. Lightning currents that have been measured in steel towers have indicated crest magnitudes, in the upper ranges, of the order of 75,000 to 190,000 amp. These figures suggest currents in the lightning stroke approaching such values.

As foreshadowed in last year's report, impulse tests on commercial transformers in the higher voltage ranges now are being made in some cases by the manufacturer as part of the routine test procedure.

During the past year the use of enclosed protective gaps has been further tried out in an effort to take lightning disturbances off transmission lines without permitting sufficient power current to flow to cause a circuit interruption. Further operating experience will be required, however, before the reliability of these devices has been proved.

From the limited experience so far available, the use of counterpoises (buried conductors) at tower bases appears to have considerable influence in reducing lightning troubles on high voltage transmission lines. Here, again, more operating experience is necessary before general conclusions can be drawn.

The continued interest of the members of the Institute in the power transmission and distribution field is a source of great gratification to the power transmission and distribution committee. The successful functioning of the committee's activities is in large part attributed to the subcommittee organization and to the initiative and interest displayed by the members.

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# Protective Devices

## ANNUAL REPORT OF THE COMMITTEE ON PROTECTIVE DEVICES*

THE COMMITTEE on protective devices has been active during the year in connection with the sponsoring of papers for the various conventions, the preparation of reports, the revision of present standards and the preparation of new standards. The organization of the committee consisted of 4 subcommittees, as follows: fault current limiting devices; lightning arresters; oil circuit breakers, switches, and fuses; and relays.

### FAULT CURRENT LIMITING DEVICES

There has been comparatively little activity in fault current limiting devices recently, though it is the intention of the committee to carry on the investigation of the Peterson coil or arc suppressor.

### LIGHTNING ARRESTERS

The lightning arrester subcommittee, working jointly with the N.E.L.A. subject committee on lightning arresters, has prepared a report covering "Present Practice in Installation and Performance of High Voltage Lightning Arresters"; this was presented at the 1933 summer convention (see ELECTRICAL ENGINEERING, v. 52, June 1933, p. 394–400).

### OIL CIRCUIT BREAKERS, SWITCHES, AND FUSES

The subcommittee on oil circuit breakers, switches, and fuses has been active in the preparation of a standard for fuses above 600 volts. There has been

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*COMMITTEE ON PROTECTIVE DEVICES: R. T. Henry, *chairman;* H. P. Sleeper, *vice-chairman;* L. E. Frost, *secretary;* Raymond Bailey, R. C. Bergvall, H. W. Collins, A. W. Copley, W. S. Edsall, J. H. Foote, S. L. Goldsborough, S. M. Hamill, Jr., T. G. LeClair, J. P. McKearin, H. A. McLaughlin, D. M. Petter, H. J. Scholz, H. K. Sels, L. G. Smith, E. R. Stauffacher, H. R. Summerhayes, B. F. Thomas, Jr., O. C. Traver, E. M. Wood, and H. B. Wood.

some difference of opinion regarding the basis of current rating. A small but active minority of the engineers in the United States have advocated rating fuses on an intermediate value that is neither the carrying capacity nor the blow-out current. This subcommittee has investigated this question and finds an almost unanimous agreement throughout the United States and Canada in favor of rating fuses on the basis of carrying capacity; the proposed standard provides for rating fuses on this basis. This standard has been recommended for publication in report form.

The subcommittee also has in preparation a standard for disconnecting, horn-gap, and knife switches, but this is being held back pending completion of the work on coördination of insulation.

### Relays

The relay subcommittee has reviewed the report on A.I.E.E. Standards No. 23 for relays which has been published in report form, and, after making certain additions and revisions, has recommended the adoption of this report as a permanent A.I.E.E. Standard. The relay subcommittee also has studied modern methods of protecting apparatus and has prepared a report giving the consensus of opinion of a large number of engineers. This material was presented at the 1933 winter convention (see "Recommended Practices for the Protection of Electrical Apparatus" Electrical Engineering, v. 51, December 1932, p. 829–34).

The principal developments in protective devices during the year have been on circuit breakers and relays. Further developments and improvements have been made on circuit breakers, principally along the line of higher operating speed and improved arc extinguishing characteristics. Further developments and improvements have been made on relays, particularly along the lines of higher speed and improved selectivity. Among recent developments in relay schemes are schemes using positive or negative phase sequence voltages or currents, and improved pilot relay schemes using communication circuits and carrier current circuits.

Among the principal activities for the coming year is the revision of the duty cycle for oil circuit breaker interrupting rating. The joint N.E.L.A.-A.E.I.C.-N.E.M.A. committee on oil circuit breakers presented a report at a meeting in Detroit, Mich., on April 5, 1933, which probably will be the basis of a revision of the duty cycle and of the derating factors for various operating duties.

# Transportation

## ANNUAL REPORT OF THE COMMITTEE ON TRANSPORTATION*

THE PRINCIPAL DEVELOPMENT of the past year in the field of heavy electric traction was the progress made by the Pennsylvania Railroad on its project for complete electrification of its lines between New York City and Washington, D. C. Electrical operation of passenger trains between New York and Philadelphia was begun on January 16, 1933, and since then has been extended to cover all New York to Philadelphia passenger service and also the New York to Washington passenger service as far as Wilmington, Del. Power is supplied from the railroad company's generating station in Long Island City, N. Y., and from 2 frequency converter stations of the Philadelphia Electric Company. In the more recent of these stations the converter units are not placed in a building but are protected by steel housings, the installation being similar to, but larger than, that made by the same company to supply the Reading Company's electrification. Single-phase transmission lines, generally 4 in number, suspended from tall H-section poles (which also support the catenary system) carry this 25-cycle power at 132-kv to step-down transformer substations, spaced from 7 to 10 miles apart along the right-of-way, from which the 11-kv contact wires are energized. Between New York and Wilmington and in the Philadelphia suburban zone approximately 72 locomotives and 382 multiple unit motor cars were in service on April 1, 1933. Including the Long Island lines, the Pennsylvania system now has 1,450 miles of electrically operated track.

The Reading Company completed the electrification of its Norristown and Chestnut Hill branches, and began electrical operation over them on February 1, 1933. Thus 46 track miles, on 22 miles of route, have been added to the mileage over which electrical operation was begun in 1931. A description of this electrification is contained in a paper at the 1932 A.I.E.E. Pacific Coast convention (see "The Reading Railroad's Suburban Electrification" by G. I. Wright, Electrical Engineering, v. 52, March 1933, p. 155–61).

The New York Central Railroad continued work on its "West Side Improvements," to remove its freight tracks from the streets of New York City south of 60th Street.

The Atchison, Topeka, and Santa Fe Railroad placed in service a 900-hp articulated gasoline-

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*COMMITTEE ON TRANSPORTATION: E. L. Moreland, *chairman;* H. L. Andrews, Reinier Beeuwkes, A. E. Bettis, H. A. Currie, J. V. B. Duer, H. H. Field, I. W. Fisk, W. A. Giger, K. T. Healy, A. B. Knowlton, H. N. Latey, John Murphy, H. Parodi, R. H. Rice, S. A. Spalding, N. W. Storer, W. M. Vandersluis, R. P. Winton, Sidney Withington, and G. I. Wright.

electric rail car, made up of 2 sections, the forward part carrying the engine, generator, and other equipment, while the other is divided into passenger and baggage compartments. This is the most powerful unit of this type that has been built. It can reach a speed of 80 mph on level tangent track and has sufficient power to handle 4 trailing coaches.

An oil-electric rail car of 600 hp has been built, which is capable of a speed of 80 mph and can haul 3 coaches. It weighs 104 tons and carries 2 300-hp diesel engines with direct-connected generators and 4 traction motors. Manufacturers state that they are now prepared to furnish units of this type with a capacity as high as 1,000 hp.

### URBAN TRANSPORTATION

The New York City Board of Transportation on September 10, 1932, placed in operation the first section of the City's independent subway system, this route being the Eighth Avenue subway, under the westerly side of Manhattan from Fulton Street to 207th Street. During 1933, operation has been extended from Fulton Street, Manhattan, under the East River to Bergen Street, Brooklyn; from 155th Street under Grand Concourse to 205th Street, Bronx; and from 53rd Street under the East River to Roosevelt Avenue, Queensborough.

In Philadelphia additional sections of subway have been placed in operation.

Additional cities have installed trolley busses so that at the close of 1932 it was reported that 280 busses were in operation in 20 cities in the United States (including Manila) over approximately 270 miles of route.

In the continuing work of developing an improved street car design, attention is being given to the elimination of vibration by using resilient wheels and rubber cushioning instead of steel springs in trucks. Another feature being developed is an eddy-current drum-type brake, incorporated in the motor frame, which will use power from the trolley. Hydraulic brakes will supplement these brakes at low speeds or when power is not available.

### RAILWAY SIGNALING

Signaling construction was much reduced during the past year, attention being given principally to small installations of automatic interlocking and centralized traffic control offering substantial economies in operation.

The first application of centralized traffic control to subway operation is being made in the extension of the Philadelphia system. A central plant at Market Street Station will control all the emergency crossovers on the new line, individual interlocking plants at the crossover locations being unnecessary; this central plant will permit complete control of all switching and traffic movement in its territory, besides furnishing visual indication of the position of trains on an illuminated track model and also making a permanent record of train movements on an automatic graphic recorder. This installation is noteworthy because of the density of traffic involved and because of modifications of design so that alternating current is used exclusively in its operation.

Signal engineering frequently must overcome difficulties presented by new developments in other lines of transportation activity. In the New York terminal zone of the Pennsylvania Railroad some tracks have been equipped with overhead contact system as well as third rail, and now are utilized for both 11-kv single-phase and 600-volt d-c operation. Saturation effects of the direct current in the alternating-current locomotive and substation transformers produce harmonics which interfered with the proper functioning of the 100-cycle track circuits controlling the wayside signals and the locomotive cab signals. This difficulty was overcome by reducing the signal circuit frequency in this area to $91^2/_3$ cycles and by modifying the design of the cab signal apparatus so that it will function properly at the lower frequency while in the terminal zone and also at 100 cycles on other sections of the road.

Another problem has been presented by the operation of light-weight rail cars, particularly those with rubber-tired or rubber-cushioned wheels, since they do not provide the low resistance connection between the rails required for shunting signal track circuits. This problem has been solved by utilizing a high frequency alternating current which is generated on the car, passed through step-down transformers having low resistance secondary windings, and then applied to the track by means of rail brushes on rubber-tired cars or through collector rings on the steel tires of rubber-cushioned wheels. The alternating current breaks down the high-resistance film on the rail surface and a low resistance path through the transformer secondaries thus is provided for shunting the track circuits.

### MARINE TRANSPORTATION

The most notable application of turbine-electric drive to new ships in the past year was in 6 vessels built for the United Mail Steamship Company (a subsidiary of the United Fruit Company). Each of these has 2 main turbine-generators, each rated at 4,200 kw, 3,500 rpm, 3,150 volts, 3-phase, unity power factor, which furnish power for 2 5,250-hp 125-rpm synchronous propelling motors. Extensive use is made of electricity to operate the auxiliaries in the engine rooms, ventilating fans, etc., throughout the ships, and all of the deck machinery.

The Manhattan, largest liner ever built in America, while driven by geared turbines, has extensive electrification of auxiliary machinery and of miscellaneous services throughout the ship. Four 500-kw turbine-generators supply 383 motors totaling nearly 4,000 hp, in addition to 1,200 fans in living quarters, 8,387 lamps, electric cooking apparatus sufficient for the preparation of 5,000 meals per day, electric clocks, automatic steering, radio, sound motion picture machinery, and many other applications. A 75-kw diesel engine driven unit also is provided for emergency use.

The 3 sister ships of the Matson Line, the Mariposa, the Monterey, and the Lurline, are equipped similarly, each having 4 500-kw turbine-generator sets and one 30-kw diesel engine-generator set, for supplying power apparatus totaling 2,600-kw, and lighting units, 230 kw.

Four new ships built for the Grace Line, to be used in its intercoastal service via the Panama Canal, also have direct geared-turbine drive; but their auxiliaries have been completely electrified, as have those on the so-called "Seatrains" operating between New York City and Havana, Cuba. These vessels, built to transport loaded freight cars, are noteworthy as the first ocean going ships on which a-c motors are used exclusively.

### VERTICAL TRANSPORTATION

The central tower of the Rockefeller Center (which is now New York City's largest building) although exceeded in height by the Empire State Building, is equipped with 74 elevators, capable of the highest speed now permitted, namely, 1,200 ft per minute. On part of these elevators an interesting application of photoelectric cells functions to prevent closing the high-speed power-operated doors while a passenger is entering.

# Report of the Board of Directors

## FOR THE FISCAL YEAR ENDING APRIL 30, 1932

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its forty-eighth Annual Report, for the fiscal year ending April 30, 1932. A general balance sheet showing the condition of the Institute's finances on April 30, 1932, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

### Death of F. L. Hutchinson, National Secretary

The Institute suffered a serious loss in the death, on February 26, 1932, of Mr. F. L. Hutchinson who had served as a member of its headquarters staff for twenty-eight years, during the last twenty of which he was the National Secretary. Information regarding his career was published on pages 202–203 of the March issue of ELECTRICAL ENGINEERING and on page 227 of the April issue.

**Directors' Meetings.**—The Board of Directors held six meetings, four in New York, one at Asheville, N. C., and one at Kansas City, Mo. The Executive Committee held a meeting in March, this being substituted for the regular March meeting of the Board, and acted upon various matters between Board Meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees, and the various officers is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

**President's Visits.**—President Skinner attended the two national conventions and two District meetings since the beginning of his administration, and visited a large number of the Sections.

The following is a list of places visited in addition to many trips to Institute headquarters in New York: Regina, Sask., and Vancouver, B. C., Canada; Seattle, Wash.; Portland, Ore.; Lake Tahoe (Pacific Coast Convention), Los Angeles, and San Francisco, Calif.; Salt Lake City, Utah; Denver, Colo.; Omaha, Nebr.; St. Louis and Kansas City (District Meeting), Mo.; Charlottesville, Va.; Washington, D. C. (A.E.C. Meetings); Detroit, Mich.; Princeton University, N. J.; Jacksonville, and Gainesville, Fla.; Atlanta, Ga.; Memphis, Tenn.; Pittsburgh, Pa.; New York, N. Y. (including Winter Convention); Mexico City, Mexico; San Antonio, Houston, Dallas, and A. & M. College, Texas; Oklahoma City, Okla.; Milwaukee (District Meeting), and Madison, Wis.; Minneapolis, Minn.; Iowa City, Des Moines, and Ames, Iowa; Chicago, and Urbana, Ill.; Indianapolis, Ind.; Philadelphia, Pa.; and Akron, Columbus, and Cleveland, Ohio. He attended the meeting of the American Association for the Advancement of Science, New Orleans, La., Dec. 28–Jan. 2, as a representative of the Institute.

In connection with these visits, he spoke at a number of meetings of neighboring Branches.

In May and June, President Skinner's visits will include the North Eastern District Meeting in Providence, the Summer Convention in Cleveland, and other Sections.

**Meetings.**—Three national conventions and two District meetings were held during the year, and a brief report on each is given below. The North Eastern District Meeting held in Rochester, New York, April 29–May 2, 1931, was included in last year's report.

**Annual Meeting.**—The Annual Business Meeting was held at the Grove Park Inn, Asheville, N. C., on Monday morning, June 22, 1931, during the annual Summer Convention. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1931, was presented, and the Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1931.

**Summer Convention.**—The forty-seventh annual Summer Convention was held at Asheville, N. C., June 22–26, 1931. Thirty-two papers were presented at seven technical sessions, and printed copies of seventeen technical committee reports were available. The annual Conference of Officers, Delegates, and Members, under the auspices of the Sections Committee and the Committee on Student Branches, was held on Monday, June 22, and Tuesday, June 23; and fifty-two Section delegates, all of the ten District Secretaries, and eight Counselor delegates were present. The entertainment features included golf and tennis tournaments, a dinner, a banquet, and various trips. The Lamme Medal, awarded by the Institute, was presented to Dr. William J. Foster at the Annual Business Meeting. More than 500 members and guests attended the convention.

**Pacific Coast Convention.**—The twentieth Pacific Coast Convention was held at Lake Tahoe, California, August 25–28, 1931. At four technical sessions, seventeen papers were presented. Twelve technical papers by students were presented at two additional sessions. The program included various social events and trips. The registration was 247.

**Winter Convention.**—The twentieth Winter Convention was held in New York, January 25–29, 1932. Sixty-three papers were presented at fourteen sessions. At an evening session, the John Fritz Medal was presented to Dr. Michael I. Pupin, and the Edison Medal was presented to Dr. E. W. Rice, Jr. Numerous inspection trips, a smoker, and a dinner-dance were held. The registration was 1429.

### District Meetings

| District No. | Location | Dates | Papers | Registration |
|---|---|---|---|---|
| 7 | Kansas City, Mo. | Oct. 22–24, 1931 | 18 | 411 |
| 5 | Milwaukee, Wis. | Mar. 14–16, 1932 | 16 | 552 |

Papers were presented at District meetings by students as follows: Kansas City 10 and Milwaukee 10. A Conference on Student Activities was held at each of the two meetings listed above.

**Sections.**—Nearly all Sections carried on a normal amount of activity, and the programs included the usual wide variety of interesting and important subjects.

The formation of a Montana Section was authorized by the Board of Directors on June 24, 1931, and the Section was organized in the summer with the entire state as its territory. This brought the number of Sections to 60.

The group activities of the Chicago and New York Sections were continued with excellent results.

The Chicago Section and other local engineering groups continued the arrangements for post-college education of engineers which were begun in 1929. A review of these activities was published on pages 280–81 of the April issue of ELECTRICAL ENGINEERING.

President Skinner visited a large number of Sections (see names under heading "President's Visits"), and will visit others later.

Resolutions were adopted by the Board of Directors, October 23, 1931, urging the Sections to consider organizing engineers' unemployment relief committees in coöperation with other engineering groups. Reports received from the Sections indicate that a large number of them have participated in the development of plans which seem adequate to meet the local needs.

The excellent methods developed by many of the Sections for maintaining close contacts with neighboring Student Branches have been continued, and the results become increasingly apparent as more and more of the students who have participated in them become active members of the Sections.

**Student Activities.**—The interest in the Student Branch activities which has been so marked for the last two or three years is still as lively as ever, as is evidenced by the number of meetings held and the large number of student papers delivered. There is no doubt that this form of activity of the Student Branches, if continued, is destined to produce electrical engineers who can write good technical papers and present them clearly and effectively.

In addition to attempting to give the electrical engineering students training and acquaintanceship with the activities of the Institute while they are still in college, the Committee on Student Branches has also for a year been working on the problem of improving the grade of student who applies for courses in electrical engineering in the educational institutions. This year the committee prepared a thirty-two page booklet describing the various kinds of work which electrical engineers are doing and giving the characteristics, training, and education which a young man should have in order to become an electrical engineer. The objects of this booklet are to encourage those who should go into this branch of engineering and discourage those who are unfitted.

Following a distribution of two copies of this booklet to each of a selected list of fifteen hundred of the leading high schools in the country, and single copies to Section and Branch officers and Branch Counselors, requests for about nine thousand copies were received. Because of the widespread and enthusiastic approval which this booklet received, the Board of Directors authorized the printing of an additional ten thousand copies.

The Engineering Foundation is preparing to publish a pamphlet containing information on the main divisions of engineering. The Committee on Student Branches has contributed the chapter on electrical engineering.

For some time the committee has been at work upon ways and means of getting Student Branches interested and informed upon the problems of safety. Plans for this work are nearly completed, and are about to be launched.

### Section and Branch Statistics

| | For Fiscal Year Ending | | | |
|---|---|---|---|---|
| | April 30 1926 | April 30 1928 | April 30 1930 | April 30 1932 |
| SECTIONS | | | | |
| Number of sections | 51 | 52 | 56 | 60 |
| Number of Section meetings held | 405 | 431 | 480 | 497 |
| Total attendance | 58,959 | 64,276 | 84,615 | 105,325 |
| BRANCHES | | | | |
| Number of Branches | 86 | 96 | 106 | 109 |
| Number of Branch meetings held | 714 | 915 | 1,009 | 1,135 |
| Total attendance | 35,270 | 44,334 | 50,401 | 54,197 |

**Technical Program Committee** (Formerly Meetings and Papers Committee).—The more important activities of the Technical Program Committee for the year 1931–32 have been the arrangement of technical programs for national conventions, coöperation with District committees in arranging programs for District meetings, and review of technical papers.

As an aid to judgment in arranging technical programs, an analysis was made during the year of the character of the material presented during the preceding three years. This showed that some subjects had been accorded very little attention in Institute papers in comparison with others. For example, considering only national conventions for the three-year period, the analysis showed that there were 62 and 50 papers, respectively, on Power Transmission and Distribution, and Electrical Machinery, while there was but one paper on Education, none on Electrochemistry and Electrometallurgy, and but three on the Production and Application of Light. In view of this, the Committee endeavored more fully to meet the broad needs and interests of the membership by encouraging greater activity in the fields that had been receiving relatively little treatment.

Gratifying results were experienced from the Committee's efforts to plan programs earlier than had been practicable in the past and to obtain authors' manuscripts well in advance of the meeting for which they were proposed.

In the interest of the Institute, as well as of the papers themselves, the Committee sought the coöperation of authors in keeping technical papers as short as was consistent with an adequate treatment of the subject discussed. As a consequence, the average length of convention papers last year was more than half a page shorter than in the previous year. The conciseness of the papers resulting from this abridgment has, it is believed, contributed to wider attention to them on the part of the membership, and it has also permitted the publication of a larger number of papers than would otherwise have been possible. Budget limitations did not, however, permit the publication of all papers offered and the presentation of papers without publication was encouraged. In some cases, authors of papers provided preprints for the use of those attending the meeting.

An effort was made to improve the general interest in technical sessions, particularly at national conventions, by assisting the authors to become thoroughly informed regarding the material and method of presentation which would be most interesting with due regard to the time available for presentation.

The Committee reviewed 210 papers during the year, of which 163 were presented. Others are awaiting scheduling for further meetings. Of the total number, 113 have been recommended for publication in TRANSACTIONS and several for publication in ELECTRICAL ENGINEERING. Only a few of the papers submitted were rejected.

Three national conventions and two District meetings were held during the year. A total of 163 papers were presented, including 17 annual reports of technical committees, as compared with a total of 229 papers presented last year. This decrease is due largely to the fact that only two District meetings were held as compared with five in the previous year. The attendance at the three national conventions was about 25 per cent less than it was during the previous year, but the Summer and Pacific Coast Conventions were held in relatively sparsely populated sections of the country. The Winter Convention attendance showed only an 11 per cent decrease from that for the previous year, which was good in the light of present conditions. Details regarding the attendance and numbers of papers presented at the various meetings are given in the accompanying table.

In order to permit the greater part of the time available for Technical Program Committee meetings to be devoted to the discussion and consideration of broader matters, the chairmen of the technical committees crystallized the programs for the sessions they were sponsoring prior to the committee meeting and the Institute Headquarters staff prepared in detail the programs proposed for the different meetings.

On the whole, good progress was made in the Technical Program Committee work. The opportunities presented at the committee meetings for the broader consideration of the more important problems involved in the Committee's work marked a distinct step forward. Record is here made of the effective work and splendid coöperation throughout the year by both the technical committees and the Headquarters staff.

ATTENDANCE AND NUMBERS OF PAPERS PRESENTED AT CONVENTIONS AND MEETINGS

MAY 1, 1931, TO APRIL 30, 1932

| | No. papers presented | No. pages printed | No. papers recommended for TRANS. | No. of sessions | Attendance |
|---|---|---|---|---|---|
| NATIONAL CONVENTIONS | | | | | |
| Summer Convention, Asheville, N. C., June 22–26 | 49* | 367 | 31 | 7 | 542 |
| Pacific Coast Convention, Lake Tahoe, August 25–28 | 17 | 168 | 10 | 4 | 247 |
| Winter Convention, New York, January 25–29 | 63 | 411 | 52 | 14 | 1,429 |
| Total | 129 | 946 | 93 | 25 | 2,218 |
| DISTRICT MEETINGS | | | | | |
| South West District, Kansas City, October 22–24 | 18 | 140 | 10 | 4 | 411 |
| Great Lakes District, Milwaukee, March. 14–16 | 16 | 113 | 10 | 3 | 552 |
| Total | 34 | 253 | 20 | 7 | 963 |
| Grand total | 163 | 1,199 | 113 | 32 | 3,181 |

* Includes 17 Technical Committee Reports.

**Publication Committee.**—Recognizing that the Institute, to keep growing, must be alive to the changing requirements of its members; recognizing that the Institute's activities and publications to serve adequately must be alive to changing conditions; and recognizing that the monthly publication constitutes the main channel through which institute members may conveniently and effectively keep informed as to current technical and professional developments and the Institute's participation therein, the Committee selected the monthly publication as representing the logical field in which to pioneer the development of increased and more effective publication service to members. As for the program embraced in the new publication policy as adopted in 1930, comments received from Institute members throughout the country have indicated to the committee that ELECTRICAL ENGINEERING for sixteen months (including April 1932) has been meeting with increasing effectiveness the requirements of the situation. In sixteen consecutive issues, ELECTRICAL ENGINEERING has carried to the membership comprehensive abstracts of 127 Institute papers, 169 articles conveying either the entire or the essential substance of an equal number of Institute papers, 79 timely articles of a special character, selected to give a better balance to the published material, 17 official reports of technical committees, and comprehensive and timely news reports of all Institute District meetings, conventions, and other important activities.

With the April 1932 issue, still further physical improvements were effected in ELECTRICAL ENGINEERING and its production procedure. As a result of an exhaustive investigation conducted by the editorial staff, all the mechanical processes were consolidated and transferred to a new and larger plant removed from New York's congested metropolitan area and devoted primarily to scientific and technical periodicals. Also, new paper of high quality and softer finish was adopted to improve readability and materially reduce eyestrain resulting from reflected light. Of importance and significance in connection with these improvements is the fact that, at the same time, production costs were materially reduced.

The monthly publication, ELECTRICAL ENGINEERING, is well understood to be one of the Institute's most important services to its every member. Therefore, its publication committee and staff are determined to leave untried no efforts that may make this service more widely useful and more definitely valuable. It will continue to pioneer the way in the direction of greater and more effective publication service to Institute members.

Other matters, of course, have occupied the Committee's attention, including more or less routine in connection with the publication of TRANSACTIONS and advance pamphlets. TRANSACTIONS, of course, is now continuing as a quarterly publication providing the usual record publication for formally accepted Institute papers and related discussion. The advisability of continuing past practice in connection with the publication of advance pamphlets has been questioned, and the committee is undertaking to investigate the situation thoroughly. Data are being collected and several experiments are under way or contemplated. For the present, however, no conclusions have been reached, and no change in policy has been made or recommended. Investigations are planned to be carried forward in an effort to determine the possibilities for improved and better coördinated publication service.

**Coördination Committee.**—In accordance with its past practice, the Committee corresponded with District and Section officers to obtain their views regarding national conventions and District meetings desired in their respective Districts during the year 1933. The complete schedule of 1933 meetings which the Committee recommended to the Board of Directors was approved on January 27, 1932.

After considering recommendations made at the Conference of Officers, Delegates, and Members, June 23, 1931, concerning methods of encouraging members who are qualified for transfer to the higher grades to submit their applications, the Committee recommended the appointment of a national standing committee on transfers and the encouragement of the appointment by each Section of a suitable committee. These recommendations were approved by the Board of Directors on January 27, 1932. The national committee has been appointed, and many of the Sections have appointed their committees.

The Committee recommended some revisions of the rules governing the award of national and District prizes and these were approved by the Board of Directors on January 27, 1932.

Various other matters referred to the Committee by the Board of Directors and the National Secretary were considered.

**Standards Committee.**—During the past year, the Standards Committee has been engaged chiefly in matters of coördination of going projects and revision of existing standards. In the development of new projects, the Committee has depended almost entirely on the technical committees of the Institute, and through them there has been presented a number of revisions of existing standards, and one new project "Electrical Recording Instruments"; also a subcommittee of the Standards Committee has developed a proposed "Standard for Relays." One feature of particular interest during the year was the publication of a report on a proposed "Test Code for Transformers," which it is expected will be followed by test codes now being developed by the Committee on Electrical Machinery for other types of apparatus.

Standardization work in coöperation with the American Standards Association has developed rapidly. The plan for coördination of standardization activities in the entire electrical field, which was fostered by the Institute and calls for centralization in the Electrical Standards Committee, actually got under way in a meeting in October 1931, at which the Electrical Standards Committee superseded the Electrical Advisory Committee. The Institute continued its representation on some thirty sectional committees, acting under the auspices of other sponsor organizations, and holds sole sponsorship for eight projects and of a number of joint relationships. With regard to the joint sponsorship projects, it should be noted that there is a very definite tendency to urge that such undertakings be placed under the sole sponsorship of the Electrical Standards Committee, and in certain cases the Institute has agreed to this on the recommendation of the Standards Committee.

Another trend now in evidence is indicated in the consolidation of sectional committees whose scopes cover closely related types of apparatus. Both of these movements, it is hoped, will tend to expedite work which has been slow in developing, largely because of the complicated procedure involved in plural sponsorships, and will also economize in the man-hours required to carry on the work. A number of sectional committees under A.I.E.E. sponsorship or joint sponsorship have submitted reports for approval to A.S.A., notably "Mercury Arc Rectifiers," "Scientific and Engineering Symbols and Abbreviations" and "Insulated Wires and Cables." The report on the proposed American Standard for "Abbreviations for Scientific and Engineering Terms" which has been under discussion for some time, and was referred by the Board of Directors to the Publication Committee for final action, was approved by that body at its April meeting. Because of the large number of organizations interested and the immense amount of detail involved, the Sectional Committee on Electrical Definitions found it necessary to postpone the issuance of its first report, and arrangements have now been made to make this very extensive project available in report form during the first half of this year. Finally, the Institute has referred to A.S.A. several of its existing Standards and Reports on Standards which have reached the point where it would seem they are ready for action by the Electrical Standards Committee.

**Committee on Code of Principles of Professional Conduct.**—A resolution adopted by the American Institute of Consulting Engineers condemning the practice of public officials and corporations in soliciting bids from engineers for services to be rendered and the practice of engineers of responding to such invitations was referred to the Committee by the Board of Directors. Upon the recommendation of the Committee, the Board of Directors adopted resolutions, at its December 4, 1931, meeting, endorsing in principle the resolution of the American Institute of Consulting Engineers, and urging members of the Institute to oppose such practices and to give their support to suitable methods of emphasizing the importance of selecting engineers on the basis of their qualifications for the work under consideration. (See ELECTRICAL ENGINEERING, January 1932, p. 55.)

**Committee on Legislation Affecting the Engineering Profession.**—Upon the recommendation of the Special Committee on Institute Policies, and with the concurrence of Chairman Kidder of the Committee on the Engineering Profession, the name of the latter committee was changed by the Board of Directors to "Committee on Legislation Affecting the Engineering Profession," and a new standing "Committee on the Economic Status of the Engineer" was appointed. This action was taken in order that the large number of important matters which would ordinarily come before a committee dealing with the engineering profession might be divided, thus enabling the committee now known as Committee on Legislation Affecting the Engineering Profession to devote its principal efforts to those legislative activities which, as the name of the Committee implies, may have a bearing on the engineering profession.

**Committee on the Economic Status of the Engineer.**—The appointment of this Committee was authorized by the Board of Directors, on June 24, 1931, as a result of the recommendations mentioned in the preceding paragraph.

The Committee recommended to the Board of Directors the adoption of a resolution urging that all Sections of the Institute coöperate with other engineering groups in the formation of local engineers' committees to promote employment and the relief of unemployed engineers. The resolution was approved by the Board of Directors on October 23, 1931, and was transmitted to the Sections promptly.

The Committee considered various other matters which had been referred to it.

**U.S. National Committee of the I.E.C.**—The U.S. National Committee of the International Electrotechnical Commission has, during the past year, been reorganized for the purpose of making it an integral part of the new scheme of standardization in the electrical industry which centers in the Electrical Standards Committee. In order to do this the power of appointing members of the U.S. National Committee, which was originally held solely by the A.I.E.E., but afterward by other constituents of the electrical industry as well, has been surrendered to the Electrical Standards Committee, except that the American Society of Mechanical Engineers continues to exercise its right of direct appointment. The membership of the Committee as reorganized consists of, first, the members of the Electrical Standards Committee, second, members appointed by the American Society of Mechanical Engineers, third, members selected by the Electrical Standards Committee in view of their knowledge and experience and competency in the international aspects of electrical standardization.

It is believed that the new arrangement will be very advantageous, inasmuch as, through this direct affiliation with the E.S.C., the I.E.C. will look to that authoritative body as a source of advice and instructions in regard to standardization in the electrical field. Furthermore, its technical work can be executed to a large extent by existing sectional committees or others to be appointed. Because of these facts and because of the official connection thereby constituted between the U.S.N.C. and the American Standards Association, whereby the machinery and the financial support of the A.S.A. become available, the U.S.N.C. will, it is believed, be able to operate more efficiently and to speak at international meetings with greater authority in regard to American matters.

The following officers of the committee have been elected:

C. O. Mailloux, Honorary President; C. H. Sharp, President; C. R. Harte and H. S. Osborne, Vice-Presidents; P. G. Agnew, Secretary; and J. W. McNair, Asst. Secretary.

In technical matters the past year has seen meetings of two of the International Advisory Committees:

1. The Advisory Committee on Electrical and Magnetic Magnitudes and Units met in London in September last, reaffirmed the decisions reached at Oslo, 1930, on magnetic units which had been questioned in certain quarters, and made arrangements for coöperation on these matters with a committee of the International Physical Union.

2. The Advisory Committee on Lamp Caps and Sockets met in Cambridge, September 1931, and decided to recommend to the I.E.C. that the American Standard dimensions for the Edison screw base and socket should be recognized as I.E.C. standards in addition to the corresponding standards already adopted at the Oslo meeting.

At the request of the French National Committee, the U.S.N.C. formed a committee for the purpose of organizing American participation in the International Electrical Congress which is to be held in Paris, July 4–12, 1932. This Committee, the Chairman of which is Dr. A. E. Kennelly, and the Secretary, Dr. H.

Pender, has arranged for a large number of important papers and reports from this country to be presented at that Congress. As the first International Electrical Congress to be held since the St. Louis Congress in 1903, and marking the period of 50 years since the first Electrical Congress, this Congress promises to be an important event in electrical history.

**Technical Committees.**—Reports of technical committees embracing an outline of the year's work and a summary of progress in the industry will be presented at the annual Summer Convention and printed in ELECTRICAL ENGINEERING and the TRANSACTIONS.

**Membership Committee.**—In the fall of 1931, the Membership Committee sent out the customary letter to all members of the Institute pointing out that during the coming year, probably more than at any other time, it was of utmost importance for every member loyally to support the activities of the Institute and to do his utmost in helping secure new members. Each member was asked to fill in a form giving the names of five prospects, and send it to the chairman of the membership committee of his Section, whose name and address were given in an accompanying folder. This plan reduced the handling cost, and saved considerable time. Hence, it has been found more satisfactory than having the forms mailed to Headquarters for distribution to the Sections.

In order to encourage each Section to establish some suitable system for keeping records of members and prospects and for transferring accurate information to its incoming committee each year, the National Committee distributed copies of a report explaining in detail the systematic and businesslike membership program adopted by the Pittsburgh Section several years ago, which has been used very successfully. It was requested that each Section adopt some definite membership policy, the so-called "Pittsburgh Plan," a modification thereof, or an entirely different method better suited to the particular requirements of the Section.

The response to this request has been most gratifying. Many of the Sections adopted the Pittsburgh Plan in its entirety, while others used modifications thereof. In addition, several Sections amplified the plan to include a definite procedure for soliciting the advancement of qualified members to higher grades. It is the intent of the Committee to request a definite report from each Section as to the actual plan adopted, results obtained, and modifications suggested. It is hoped that from these reports the Membership Committee will be able to prepare a simple yet effective membership routine which will be submitted to the Institute for consideration as a national policy.

Despite the general business conditions, 1,391 applications for admission were received. The additions to and deductions from the membership during the year are given in the following table. The total membership as of April 30 is 17,550.

| | Honorary | Fellow | Member | Associate | Total |
|---|---|---|---|---|---|
| Membership on April 30, 1931 | 10 | 751 | 3,848 | 13,725 | 18,334 |
| Additions: | | | | | |
| Transferred | ..... | 12 | 161 | ..... | |
| New members qualified | ..... | 2 | 81 | 1,094 | |
| Reinstated | ..... | ..... | 8 | 24 | |
| Total | 10 | 765 | 4,098 | 14,843 | 19,716 |
| Deductions: | | | | | |
| Died | 1 | 17 | 30 | 57 | |
| Resigned | ..... | 4 | 82 | 572 | |
| Transferred | ..... | ..... | 9 | 164 | |
| Dropped | ..... | 6 | 106 | 1,118 | |
| Membership on April 30, 1932 | 9 | 738 | 3,871 | 12,932 | 17,550 |

**Deaths.**—The following deaths have occurred during the year:

*Honorary Member:* Thomas Alva Edison.

*Fellows:* Thomas H. U. Aldridge, Frank G. Baum, Bernard A. Behrend, Joseph Bijur, H. Eugene Chubbuck, Charles L. Edgar, Joens E. Fries, Francis M. Hartmann, Carlyle Kittredge, William E. Richards, Lewis T. Robinson, Harold B. Smith, Samuel W. Stratton, Lewis S. Streng, Edward Taylor, Edward W. Trafford, Donald F. Whiting.

*Members:* Edward G. Acheson, George M. Bates, Oliver J. Bushnell, Edward J. Condon, John R. Cowley, George G. Cree, Harry P. Davis, William I. Donshea, Benson O. Ellis, William H. Fernholz, John A. Foerster, Thomas Foulkes, Truman P. Gaylord, Brace H. Hamilton, Jesse Harris, Frederick L. Hutchinson, Jeremiah J. Kennedy, Gifford LeClear, Max Neuber, George M. Ogle, Harold G. Payne, William D. Pomeroy, C. M. Roswell, Herbert R. Rowland, Howard R. Sargent, William F. Smith, Hans C. Specht, Jay L. Stannard, Max Toltz, Alexander J. Wurts.

*Associates:* Edward D. Adams, Cedric S. Anderson, Marvin C. Ansteth, Clark E. Baker, Willis H. Banks, Joseph T. Blondin, James W. Brown, William H. Bullock, Roy R. Burkholder, William F. Callahan, Harold Calvert, Rufus N. Chamberlain, Bradley L. Child, Isabelle W. Conlin, John B. Cornell, Delbert M. Cross, Charles Day, Alva C. Dinkey, Leslie C. Dobson, Clyde Drake, W. Bryan Duncan, Earl G. Eggler, G. H. Finks, Bruce Ford, Melville W. Fuller, Louis R. Gatchell, James J. Green, John P. Gregory, Stanley E. Heisler, Adolf O. Heyden, Horace Hinz, G. Vernon Hobbs, Engelhardt W. Holst, Leslie Killam, John J. Larkin, Isaac N. Lewis, Edward K. Lewison, Henry Lieberman, John D. Lindstrom, Charles E. Long, Raymond S. Masson, Carl Leo Mees, J. Walter Miles, Joseph F. Morris, John D. Nies, Christian Nyholm, Jan D. Otten, W. S. Richmond, Arno A. Rohde, Charles F. Royce, Otto E. Vogt, D. A. Wadia, Cyril T. Wall, Lewis J. Wells, Bertram P. Wilber, Stanley Wokis, Edward O. Zwietusch.

**Board of Examiners.**—The Board of Examiners held nine meetings during the past year, averaging about two and one-quarter hours. A total of 3,229 cases were considered, divided as shown in the following table:

| | | |
|---|---|---|
| APPLICATIONS FOR ADMISSION | | |
| Recommended for grade of Associate | 1,325 | |
| Not recommended | 11 | 1,336 |
| Recommended for grade of Member | 70 | |
| Not recommended | 9 | 79 |
| Recommended for grade of Fellow | 2 | |
| Not recommended | 1 | 3 |
| Recommended for enrolment as Students | | 1,636 |
| APPLICATIONS FOR TRANSFER | | |
| Recommended for grade of Member | 149 | |
| Not recommended | 17 | 166 |
| Recommended for grade of Fellow | 7 | |
| Not recommended | 2 | 9 |
| | | 3,229 |

**Institute Prizes.**—Four national prizes ($100 each) and ten District prizes ($25 each), for papers presented in 1930, were announced in the June 1931, issue of ELECTRICAL ENGINEERING. The national prizes were presented at the Summer Convention in Asheville, and the District prizes were presented at various meetings in the respective Districts.

**Scholarships.**—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. Each scholarship pays $350.00 toward annual tuition, with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

**Edison Medal.**—The Edison Medal, founded by associates and friends of Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1931 was awarded to Dr. Edwin Wilbur Rice, Jr., "for his contributions to the development of electrical systems and apparatus and his encouragement of scientific research in industry." The medal was presented at the Winter Convention of the Institute, January 27, 1932.

**John Fritz Medal.**—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the twenty-eighth medal to Dr. Michael Idvorsky Pupin.

**Lamme Medal.**—The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, Chief Engineer of the Westinghouse Electric & Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of two such medals in some years if the accumulation from the funds warrants.

The Lamme Medal Committee of the Institute awarded the fourth (1931) Lamme Medal to Mr. Giuseppe Faccioli, "for his contribution to the development and standardization of high-voltage oil-filled bushings, capacitors, lightning arresters, and numerous features in high-voltage transformers and power transmissions." Arrangements are being made for the presentation of the medal at the annual Summer Convention at Cleveland, Ohio, June 20–24, 1932.

**Commission of Washington Award.**—The Washington Award for 1932 was made to Dr. William D. Coolidge, "for his scientific spirit and achievement in developing ductile tungsten and the modern X ray tube."

The award is made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A.S.C.E., the A.I.M.E., the A.S.M.E., and the A.I.E.E.

**Employment Service.**—The Institute coöperates with the national societies of civil, mining, and mechanical engineers in the operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others cooperate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society, and the Engineers' Club of San Francisco.

The New York office has been coöperating closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the Employment Service announcements monthly in ELECTRICAL ENGINEERING, weekly subscription bulletins are issued for those seeking positions.

**American Engineering Council.**—This organization, now including in its membership twenty-seven national, state, and local engineering societies with a total membership of about 62,000, has continued to represent its constituents in matters affecting the public welfare and involving the engineering and allied technical professions.

During the past year, recommendations were made concerning many bills presented in the Congress of the United States, and much attention was given to methods of reducing unemployment among engineers and to studies of the causes which produced the depression. The Council had a representative on the President's Emergency Committee for Employment. Its Committee on Relief from Unemployment, and Committee on Relation of Consumption, Production, and Distribution presented comprehensive reports. The Council sponsored the formation of Committees on Engineers and Employment which were organized in nearly all of the states.

The Council's many special committees include those on: Administration of Public Works; Airports; Air Transport Service in Foreign Countries; Bridges; Communications; Competition of Governmental Agencies with Engineers in Private Practice; Corps of Engineers; Engineering Features of Public Domain Report; Engineers and Employment; Engineers Water Power Policy; Flood Control; Man-Hour Information; Membership Contributions; Muscle Shoals; Naval Towing Tank; Oil Pollution of Streams; Patents; Reforestation; Relation of Consumption, Production, and Distribution; Representation; Public Works; Street Traffic Signs, Signals, and Markings; and Water Resources and Control.

**United Engineering Trustees, Inc.**—This organization, formerly United Engineering Society, was set up by the four national societies of civil, mining, mechanical, and electrical engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the Library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual report of the United Engineering Trustees, Inc., were published on page 285 of the April 1932 issue of ELECTRICAL ENGINEERING.

**Engineering Foundation.**—This department of United Engineering Trustees, Inc., was established in 1914 by the national societies of civil, mining, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made four gifts toward its endowment. The fund has been generously increased through the gifts of Edward D. Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects and coöperation has been extended in others.

**Engineering Societies Library.**—The Library is administered as a free public library under the direction of the Library Board of United Engineering Trustees, Inc., this Board being composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers.

The Library contains about 200,000 books and pamphlets. It receives regularly about 1,200 technical periodicals in many languages, and about 800 additional publications issued irregularly.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searchers, etc. Special arrangements have been made for lending books.

**Representatives.**—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years. A complete list of representatives is published in the September and January issues of ELECTRICAL ENGINEERING.

**Finance Committee.**—During the year the Committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-Laws.

Haskins & Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the Board of Directors,

H. H. HENLINE,

*Assistant National Secretary.*

May 20, 1932.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 17, 1932.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have audited your accounts for the year ended April 30, 1932, and submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1932.
  Schedule 1—Reserve Capital Fund—Securities, Less Reserve for Bonds of Doubtful value.

B—Summary of Income and Surplus for the Year Ended April 30, 1932.

We hereby certify that in our opinion Exhibits A and B set forth the financial condition of the Institute at April 30, 1932, and the results of its operations for the year ended that date.

Yours truly,
HASKINS & SELLS

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

EXHIBIT A.

### BALANCE SHEET, APRIL 30, 1932

### ASSETS

| | | | |
|---|---|---|---|
| **REAL ESTATE:** | | | |
| One-fourth interest in Land, Building, and Equipment of United Engineering Trustees, Inc., 25 to 33 West 39th Street (depreciation carried on books of the United Engineering Trustees, Inc.) | | | $496,948.48 |
| **EQUIPMENT:** | | | |
| Library—Volumes and fixtures | | $ 39,296.37 | |
| Works of art, paintings, etc. | | 3,001.35 | |
| Office furniture and fixtures | $ 32,341.64 | | |
| Less reserve for depreciation (including ($10,361.81 funded) | 17,508.40 | 14,833.24 | |
| Total equipment | | | 57,130.96 |
| **WORKING ASSETS:** | | | |
| "Transactions," etc. | | $ 5,316.12 | |
| Text and cover paper | | 849.19 | |
| Badges | | $ 1,118.18 | |
| Total working assets | | | 7,283.49 |
| **CURRENT ASSETS:** | | | |
| Cash | | $ 14,505.84 | |
| Accounts receivable: | | | |
| Members—For dues | | 34,344.79 | |
| Advertisers | | 429.00 | |
| Miscellaneous | | 2,412.46 | |
| Accrued interest on investments | | 2,956.64 | |
| Total current assets | | | 54,648.73 |
| **FUNDS:** | | | |
| Reserve Capital Fund: | | | |
| Cash | $ 6,799.11 | | |
| Securities, less reserve for bonds of doubtful value—Schedule 1 | 185,386.75 | $192,185.86 | |
| Life Membership Fund: | | | |
| Cash | $ 6,359.09 | | |
| Chicago Burlington & Quincy Railroad 4% bonds, 1958, registered, face value, $5,000.00 | 4,868.75 | | |
| Accrued interest | 33.33 | 11,261.17 | |
| International Electrical Congress of St. Louis—Library Fund: | | | |
| Cash | $ 1,371.60 | | |
| New York City 4½% corporate stock, 1957, par value, $2,000.00 | 2,204.05 | | |
| New York Telephone Company 4½% bond, 1939, registered, face value, $1,000.00 | 878.75 | | |
| Accrued interest | 67.50 | 4,521.90 | |
| Mailloux Fund: | | | |
| Cash | $ 0.94 | | |
| New York Telephone Company 4½% bond, 1939, registered, face value, $1,000.00 | 1,000.00 | | |
| Accrued interest | 22.50 | 1,023.44 | |
| Lamme Medal Fund: | | | |
| Cash | $ 215.78 | | |
| Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C" bond, 1995, face value, $4,000.00 | 4,330.00 | | |
| Accrued interest | 100.00 | 4,645.78 | |
| Depreciation of Furniture and Fixtures Fund: | | | |
| Cash | $ 296.81 | | |
| Cleveland Union Terminals Company 5% sinking fund series "B" gold bonds, 1973, registered, face value, $4,000.00 | 4,010.00 | | |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property, Nos. 75–79 Prospect Street, East Orange, N. J.) 5½%, due 1933, face value, $1,000.00 | 1,000.00 | | |
| United Gas Improvement Company $5.00 preferred stock, 20 shares | 1,995.00 | | |
| Consolidated Gas Company of New York $5.00 cumulative preferred stock, 30 shares | 3,060.00 | 10,361.81 | |
| Total funds | | | 223,999.96 |
| Total | | | $840,011.62 |

### LIABILITIES

| | | | |
|---|---|---|---|
| **CURRENT LIABILITIES:** | | | |
| Accounts payable | | $ 8,114.28 | |
| Dues received in advance | | 2,301.63 | |
| Entrance fees and dues advanced by applicants for membership | | 310.50 | |
| Subscriptions for "Transactions" received in advance | | 126.00 | |
| Total current liabilities | | | $10,852.41 |
| **FUND RESERVES (NOT INCLUDING DEPRECIATION RESERVE):** | | | |
| Reserve Capital Fund | $204,884.61 | | |
| Less provision for reserve for bonds of doubtful value | 12,698.75 | $192,185.86 | |
| Life Membership Fund | | 11,261.17 | |
| International Electrical Congress of St. Louis—Library Fund | | 4,521.90 | |
| Mailloux Fund | | 1,023.44 | |
| Lamme Medal Fund | | 4,645.78 | |
| Total fund reserves (not including depreciation reserves | | | 213,638.15 |
| **SURPLUS**, Per Exhibit "B" | | | $615,521.06 |
| Total | | | $840,011.62 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### SUMMARY OF INCOME AND SURPLUS FOR THE YEAR ENDED APRIL 30, 1932

EXHIBIT B.

| | | | |
|---|---|---|---|
| **INCOME:** | | | |
| Dues | | *$225,245.37 | |
| Students' fees | | 10,685.75 | |
| Entrance fees | | 5,987.50 | |
| Transfer fees | | 865.00 | |
| Advertising | | 52,048.07 | |
| "Electrical Engineering" subscriptions | | 8,990.52 | |
| "Transactions" subscriptions | | 12,755.87 | |
| Sales—Miscellaneous publications | | 7,986.68 | |
| Sales—Badges | $ 2,070.25 | | |
| Less cost | 2,175.82 | †*105.57* | |
| Interest on securities in reserve capital fund | | 9,693.52 | |
| Interest on securities in depreciation reserve fund | | 549.16 | |
| Interest on bank balances | | 619.67 | |
| Total | | | $335,321.54 |
| **EXPENSES:** | | | |
| Publications: | | | |
| "Electrical Engineering" | $ 85,838.95 | | |
| "Transactions" | 21,506.18 | | |
| Technical papers | 18,616.00 | | |
| Year Book | 3,925.03 | | |
| Miscellaneous | 3,365.85 | $133,252.01 | |
| Institute meetings | | 14,841.15 | |
| Administrative expenses | | 58,147.21 | |
| President's special appropriation | | 1,926.31 | |
| Traveling expenses: | | | |
| Board of Directors | | 5,056.50 | |
| National nominating committee | | 932.65 | |
| Institute representatives | | 45.00 | |
| Sections | | 35,463.39 | |
| Geographical districts' expenses: | | | |
| Traveling expenses: | | | |
| Executive committee | $ 2,595.51 | | |
| Vice-presidents | 828.13 | | |
| District best paper prizes | 100.02 | | |
| District prizes for initial paper | 75.00 | 3,598.66 | |
| Branches | | 15,154.36 | |
| Membership | | 7,452.26 | |
| Finance | | 386.02 | |
| Forward | | $276,255.52 | $335,321.54 |

| | | |
|---|---|---|
| TOTAL INCOME—(FORWARD) | | $335,321.54 |
| EXPENSES—(FORWARD) | $276,255.52 | |
| Code committee | 60.00 | |
| Technical committees | 164.65 | |
| Committee on legislation affecting the engineering profession | 501.50 | |
| Headquarters committee | 360.50 | |
| Standards | 7,133.33 | |
| American Standards Association | 1,500.00 | |
| United States National Committee of International Electrotechnical Commission | 205.09 | |
| United States National Committee of International Commission on Illumination | 300.00 | |
| Engineering Societies Library—Maintenance | 10,093.52 | |
| Engineering Societies Employment Service | 2,701.60 | |
| United Engineering Trustees, Inc.—Assessment | 5,713.56 | |
| American Engineering Council | 16,065.82 | |
| Institute prizes | 453.44 | |
| Edison medal committee | 184.96 | |
| John Fritz medal | 324.94 | |
| Total | | 322,018.43 |
| NET INCOME | | $ 13,303.11 |
| SURPLUS CREDITS: | | |
| Increase in value of library | $ 1,500.00 | |
| Adjustment of Life Membership Reserve—Excess of fund over required amount as determined by the Institute in accordance with the by-laws | 909.61 | |
| Total | | 2,409.61 |
| GROSS SURPLUS FOR THE YEAR | | $15,712.72 |
| SURPLUS CHARGES: | | |
| Uncollectable dues and members' charges written off | $ 13,495.22 | |
| Provision for depreciation of furniture and fixtures | 2,247.13 | |
| Loss on disposal of office fittings | 64.85 | |
| Total | | 15,807.20 |
| DEFICIT FOR THE YEAR | | $ 94.48 |
| SURPLUS, MAY 1, 1931 | $601,780.04 | |
| Add amount transferred from Reserve Capital Fund in accordance with resolution of the Board of Directors | 13,835.50 | 615,615.54 |
| SURPLUS, APRIL 30, 1932 | | $615,521.06 |

*Includes $91,670.00 allocated to ELECTRICAL ENGINEERING subscriptions.

†Loss.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### RESERVE CAPITAL FUND—SECURITIES,

### LESS RESERVE FOR BONDS OF DOUBTFUL VALUE,

### APRIL 30, 1932

EXHIBIT A.
SCHEDULE NO. 1.

| | Face Value or Number of Shares | Book Value |
|---|---|---|
| **RAILROAD BONDS:** | | |
| Baltimore and Ohio Railroad Company 6% refunding and general mortgage series "C," due 1995, registered | $8,000.00 | $ 8,940.00 |
| Central of Georgia Railway Company 5 1/2% refunding and general mortgage series "B," due 1959, registered | 5,000.00 | 5,283.75 |
| Chicago and Erie Railroad Company 5% first mortgage gold, due 1982, registered | 1,000.00 | 1,105.00 |
| Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series "A" gold, due 1971, registered | 1,000.00 | 1,010.00 |
| Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage gold, due 1960, registered | 8,000.00 | 7,940.00 |
| Florida East Coast Railway Company 5% first and refunding mortgage series "A" gold, due 1974, registered (certificates of deposit) | 10,000.00 | 9,818.75 |
| Great Northern Railroad Company 5 1/2% general mortgage series "B" gold, due 1952, registered | 10,000.00 | 9.847.50 |
| New York Central Railroad Company 5% refunding and improvement mortgage series "C," due 2013, registered | 6,000.00 | 5,742.50 |
| Pennsylvania Railroad Company 4 1/2% general mortgage series "A" gold, due 1965, registered | 5,000.00 | 5,130.00 |
| St. Louis, San Francisco Railway Company 5% prior lien mortgage series "B," due 1950, registered | 6,000.00 | 5,497.50 |
| Southern Railway Company 5% first consolidated mortgage gold, due 1994, registered | 1,000.00 | 980.00 |
| Total | | $61,295.00 |
| **PUBLIC UTILITY BONDS:** | | |
| American Telephone and Telegraph 5% sinking fund gold debentures, due 1960, registered | $15,000.00 | $14,625.00 |
| Consolidated Gas Company of New York 5 1/2% gold debentures, due 1945, registered | 5,000.00 | 5,187.50 |
| Duquesne Light Company 4 1/2% first mortgage series "A" gold, due 1967, registered | 3,000.00 | 2,970.00 |
| Ontario Power Service Corporation, Limited, 5 1/2% first closed mortgage sinking fund gold, due 1950, registered | 5,000.00 | 4,711.00 |
| Pacific Gas & Electric Company 5 1/2% first and refunding mortgage series "C" gold, due 1952, registered | 5,000.00 | 5,137.50 |
| Forward | | $32,631.00 |
| Total Railroad Bonds—(Forward) | | $61,295.00 |
| Public Utility Bonds—(Forward) | | $32,631.00 |
| Philadelphia Company secured 5% series "A" gold, due 1967, registered | $10,000.00 | 10,000.00 |
| Shawinigan Water and Power Company 4 1/2% first mortgage and collateral trust sinking fund series "A" gold, due 1967 | 5,000.00 | 4,581.25 |
| Texas Electric Service Company 5% first mortgage gold, due 1960, registered | 4,000.00 | 3,910.00 |
| United Light and Power Company 5 1/2% first lien and consolidated mortgage gold, due 1959 | 5,000.00 | 4,975.00 |
| Total | | $56,097.25 |
| **INDUSTRIAL BONDS:** | | |
| American Smelting and Refining Company 5% first mortgage series "A" gold, due 1947, registered | $9,000.00 | $9,085.00 |
| Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund gold, due 1936, registered | 5,000.00 | 5,033.75 |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property Nos. 75–79 Prospect Street, East Orange, N. J.) 5 1/2%, due 1933 | 14,000.00 | 14,000.00 |
| International Match Corporation 5% convertible gold debentures, due 1941 | 3,000.00 | 2,880.00 |
| New York Steam Corporation 6% first mortgage gold, due 1947, registered | 10,000.00 | 10,837.50 |
| United States Rubber Company 5% first and refunding mortgage series "A," due 1947, registered | 2,000.00 | 1,915.00 |
| Western Electric Company 5% debentures, due 1944, registered | 10,000.00 | 9,818.75 |
| Youngstown Sheet and Tube Company 5% first mortgage sinking fund series "A" gold, due 1978, registered | 20,000.00 | 20,275.00 |
| Total | | $73,845.00 |
| **STOCKS:** | | |
| Commonwealth Edison Company | 12 shares | $ 2,892.00 |
| Public Service Corporation of New Jersey, $5.00 preferred | 30 " | 2,958.75 |
| United Gas Improvement Company, $5.00 preferred | 10 " | 997.50 |
| Total | | $ 6.848.25 |
| Total | | $198,085.50 |
| **LESS RESERVE FOR BONDS OF DOUBTFUL VALUE:** | | |
| Florida East Coast Railway Company 5% first and refunding mortgage series "A" gold, due 1974, registered | $10,000.00 | $ 9,818.75 |
| International Match Corporation 5% convertible gold debentures, due 1941 | 3,000.00 | 2,880.00 |
| Total | | $12,698.75 |
| Remainder | | $185.386.75 |

# Report of the Board of Directors

## FOR THE FISCAL YEAR ENDING APRIL 30, 1933

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its forty-ninth Annual Report, for the fiscal year ending April 30, 1933. A general balance sheet showing the condition of the Institute's finances on April 30, 1933, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

**Directors' Meetings.**—The Board of Directors held five meetings, three in New York, one in Cleveland, Ohio, and one in Baltimore, Md. The Executive Committee held meetings in December and March, they being substituted for the regular meetings of the Board, and acted upon various matters between Board meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees, and the various officers is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

**President's Visits.**—President Charlesworth attended the two national conventions and the one District meeting since the beginning of his administration, and visited a large number of the Sections.

The following is a list of places visited: Vancouver, B. C. (Pacific Coast Convention), Canada; Seattle, Wash.; Portland, Ore.; Los Angeles, and San Francisco, Calif.; Salt Lake City, Utah; Denver, Colo.; Omaha, Nebr.; St. Louis, and Kansas City, Mo.; Richmond, Va.; Jacksonville, and Gainesville, Fla.; Atlanta, Ga.; Louisville, Ky.; Birmingham, Ala.; Raleigh, No. Carolina; Cincinnati, and Columbus, Ohio; Memphis, Tenn.; San Antonio, Houston, and Dallas, Tex.; Oklahoma City, Okla.; Milwaukee, Wis.; Minneapolis, Minn.; Ames, and Des Moines, Iowa; Indianapolis, Ind.; Detroit, Mich.; Baltimore (District Meeting), Md.; Philadelphia, and Pittsburgh, Pa.

In connection with these visits, he spoke at several meetings of neighboring Branches.

In May and June, President Charlesworth's visits will include the North Eastern District Meeting in Schnectady, the Summer Convention in Chicago, and other Sections.

**Meetings.**—Three national conventions and two District meetings were held during the year, and a brief report on each is given below.

**Annual Meeting.**—The Annual Business Meeting was held at the Hotel Cleveland, Cleveland, Ohio, on Monday morning, June 20, 1932, during the annual Summer Convention. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1932, was presented, and the Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1932.

**Summer Convention.**—The forty-eighth annual Summer Convention was held at Cleveland, Ohio, June 20–24, 1932. Thirty-nine papers were presented at ten technical sessions, and printed copies of thirteen technical committee reports were available. The annual Conference of Officers, Delegates, and Members, under the auspices of the Sections Committee and the Committee on Student Branches, was held on Monday, June 20, and Tuesday, June 21, and forty-nine section delegates, nine District Secretaries, and seven Counselor delegates were present. The entertainment features included golf and tennis tournaments, two dinners, old-time party, and various trips. The Lamme Medal, awarded by the Institute, was presented to Giuseppe Faccioli at the Annual Business Meeting. 1,022 members and guests attended the convention.

**Pacific Coast Convention.**—The twenty-first Pacific Coast Convention was held at Vancouver, B. C., Canada, August 30–September 2, 1932. At four technical sessions, fourteen papers were presented. Eleven technical papers by students were presented at two additional sessions. The program included various social events and trips. The registration was 300.

**Winter Convention.**—The twenty-first Winter Convention was held in New York, January 23–27, 1933. Fifty-eight papers were presented at fourteen sessions. At an evening session, the Edison Medal was presented to Bancroft Gherardi. Numerous inspection trips, a smoker, and a dinner-dance were held. The registration was 1,099.

**District Meetings.**—

| District No. | Location | Dates | Papers | Registration |
|---|---|---|---|---|
| 1 | Providence, R. I. | May 4–7, 1932 | 18 | 252 |
| 2 | Baltimore, Md. | Oct. 10–13, 1932 | 13 | 240 |

Six student papers were presented, and a Conference on Student Activities was held at the District Meeting in Providence.

**Sections.**—Despite the unfavorable economic conditions, the sixty Sections have carried on a normal amount of activity, with the usual wide variety of interesting and important subjects presented at the meetings.

The group activities of the Chicago and New York Sections continued to produce excellent results, and the conduct of classes for the post-college education of engineers, started in 1929, were continued by the Chicago Section in coöperation with other local groups.

President Charlesworth visited a large number of Sections (see heading "President's Visits"), and will visit others later.

Many Sections have participated in arrangements for the relief of unemployed engineers.

The excellent plans developed by a considerable number of Sections for maintaining close contacts with neighboring Branches and for encouraging the participation of younger members in Section meetings have been continued in operation with gratifying results.

**Student Activities.**—The Student Branches during the past year have had a busy season in spite of the period of delayed prosperity. They have continued to place their main emphasis upon papers or talks delivered by students rather than listening to outside speakers and watching moving pictures.

The large number transferring from the grade of Student of the A.I.E.E. to Associates has been gratifying, especially at a time when so many former members found it necessary to relinquish their membership.

In an effort to increase the number of Students of the A.I.E.E., a subcommittee of the Committee on Student Branches has been appointed to study the present organization of Student Branches and recommend, if possible, a type of organization which will encourage, even more than the present arrangement, students in electrical engineering to become affiliated directly with the Institute. This subcommittee is to render a report at the Summer Convention.

New Branches were organized at the George Washington University, Washington, D. C., and the University of Porto Rico, Mayaguez, Porto Rico.

### Section and Branch Statistics

| | For Fiscal Year Ending | | | |
|---|---|---|---|---|
| | April 30 1927 | April 30 1929 | April 30 1931 | April 30 1933 |
| SECTIONS | | | | |
| Number of sections | 52 | 54 | 59 | 60 |
| Number of section meetings held | 431 | 460 | 491 | 498 |
| Total attendance | 60,708 | 73,254 | 108,523 | 73,806 |
| BRANCHES | | | | |
| Number of branches | 95 | 100 | 109 | 111 |
| Number of branch meetings held | 842 | 940 | 1,137 | 1,026 |
| Total attendance | 42,650 | 47,408 | 51,807 | 59,439 |

**Technical Program Committee.**—One of the most important phases of the work of the Technical Program Committee throughout the year 1932–33 has been the establishment of technical programs for national conventions to best meet the broad needs of the membership. The committee has also assisted District committees by providing papers for District meetings. Analyses of the subject matter contained in the papers, the number of papers presented, and the attendance at the three national conventions and two District meetings held during the year indicate that most gratifying results have been attained. In addition to the selection of papers for national conventions, their review, and recommendations for publication, the Conduct of Technical Sessions has been revised and, as requested by the Board of Directors, a statement of policy in regard to papers by non-member authors has been prepared for the consideration of the Board.

As stated in the report of a year ago, an analysis was made of the character of the material presented during the preceding three years, which indicated that but one paper in the field of education and none in the field of electrochemistry and electrometallurgy had been presented. To fill the need along educational lines two important addresses on education were delivered by prominent speakers, one at the Summer Convention in Cleveland, and the other at the Winter Convention in New York. In addition, three valuable papers by well-known authors on educational work were presented. In the field of electrochemistry and electrometallurgy several contributions were made in sessions held at each of these conventions.

The committee reviewed 208 papers during the year, of which 160 were presented. Some papers are awaiting scheduling for future meetings, and only a few of the papers submitted were returned to the authors. Of the total number presented, 121 were recommended for publication in the TRANSACTIONS and several for publication in ELECTRICAL ENGINEERING. While the total number presented was only three less than the number presented during the previous year, a reduction in the average number of pages per paper has been brought about by careful reviewing and the close coöperation of the authors, so that 217 less pages were required for publication. The total attendance at the three national conventions was 2,422, an increase of 9.2% over the attendance for these three conventions the previous year. This was mainly attributable to the splendid attendance of over 1,000 at the Cleveland Summer Convention. The grand total attendance for the three national conventions and two District meetings held throughout the year was 2,914, only $8^1/_2$% less than that for the previous year, which is considered extremely good in the light of present business conditions. Details regarding attendance and the number of papers presented and recommended for publication are given in the attached tabulation.

Through the coöperation of several members of the committee, three men worked with the Secretary during the Winter Convention, taking care of various details in connection with conduct of technical sessions. It was felt that, as a result of their efforts, the sessions were conducted more smoothly and, in addition, those in attendance were kept informed as to the papers and discussions which were being presented in another parallel session.

Consideration has been given by the committee to the suggestion that small meeting rooms be provided during the conventions, so that authors and those interested may get together informally to resume discussions of papers in cases where time limitations require interrupting discussion at the formal technical session. The Conduct of Techical Sessions has been revised to meet this objective, and rearranged with the view toward making its recommendations more pointed.

In view of the objections raised in the past to the presentation of papers by non-member authors, the committee has been mindful of the situation and reduced the number of papers by non-members on programs throughout the year. In accordance with instructions of the Board of Directors, the committee has prepared a suggested statement of policy to apply also to District committees, which, it is felt, will have the effect of still further reducing the number of papers presented by non-members, without excluding information for the membership as to developments in the electrical arts and sciences and in closely allied fields.

The committee wishes to record herein the splendid coöperation shown by authors and members of the various technical committees. It is also a privilege to record here the effective and constructive work of the Institue headquarters staff and, in particular, the Secretary of this committee.

ATTENDANCE AND NUMBERS OF PAPERS PRESENTED AT CONVENTIONS AND MEETINGS

April 30, 1932, to April 30, 1933

| | No. papers presented | No. pages printed | No. papers recommended for Trans. | No. of sessions | Attendance |
|---|---|---|---|---|---|
| National Conventions | | | | | |
| Summer Convention Cleveland, Ohio, June 20–24, 1932 | 52* | 257 | 31 | 10 | 1,022 |
| Pacific Coast Convention, Vancouver, B. C., August 30–September 2, 1932 | 14 | 89 | 9 | 4 | 300 |
| Winter Convention, New York, January 23-27, 1933 | 58 | 385 | 54 | 14 | 1,100 |
| Total | 129 | 731 | 94 | 28 | 2,422 |
| District Meetings | | | | | |
| North Eastern District, Providence, R. I., May 4–7, 1932 | 18 | 130 | 15 | 4 | 252 |
| Middle Eastern District, Baltimore, Md., October 10–13, 1932 | 13 | 121 | 12 | 4 | 240 |
| Total | 31 | 251 | 27 | 8 | 492 |
| Grand Total | 160 | 982 | 121 | 36 | 2,914 |

* Includes 13 technical committee reports.

**Publication Committee.**—The Institute's technical publication service remains a subject of wide discussion throughout the membership. Realizing that this service represents the principal tangible return to the individual member for the dues that he pays, continuing attention has been given to possible improvements. Some contemplated developments, of course, were arrested as a result of necessary budget reductions, a condition that turned primary attention to logical ways and means of maintaining a satisfactory level of publication service in spite of necessary economies. Further exhaustive studies in this same direction now are under way with the expectation that they will be completed soon and that the results and conclusions gained therefrom will establish a basis that will enable further constructive development in publication policy and practice, taking fully into account present economic conditions.

During the fiscal year that ended April 30, 1933, the evolution of the monthly, ELECTRICAL ENGINEERING, was continued as the principal channel of contact with Institute members and the vehicle through which they may keep well informed as to current professional and technical developments, and the Institute's activity in such fields. In 12 issues there were given comprehensive abstracts of 121 Institute papers, 86 feature articles conveying at least the principal substance of that number of Institute papers, and 56 special and 11 miscellaneous articles selected to give a better balance to the published material. In addition, 13 technical committee reports and comprehensive news reports of all conventions, District meetings, and other important activities were included.

The QUARTERLY TRANSACTIONS, of course, was continued as the usual record publication for formal Institute papers and discussion thereon. The advisability of continuing traditional practice in connection with the publication of advance pamphlets of technical papers remains an open question which, as previously indicated, along with other questions of policy and practice, is being studied in an effort to improve publication service.

**Standards Committee.**—Following a practice agreed upon for the preceding year, the Standards Committee has confined this past year's meetings to four—one each in October, January, April, and June. Within the Institute itself, active work is continuing in the development of proposed standards and codes through the medium of the interested technical committees. The Committee on Electrical Machinery has submitted revisions of the standards for capacitors, constant current transformers, and for the standards in the rotating machinery group. It has also developed the second of the series of test codes, that for synchronous machines. This was published in report form in January, 1933. The Committee on Instruments and Measurements has offered a draft of a proposed standard on recording instruments to be published shortly, and is at work on revisions of the standards for electrical measuring instruments and instrument transformers. The Committee on Protective Devices likewise has proposed standards in course of development, among which may be mentioned fuses and knife switches. Subcommittees of the Standards Committee have in hand proposed relay standards, and are at work on questions with regard to reactive power.

Within the American Standards Association, many sectional committees are engaged in developing American Standards in the electrical field, and have largely as a basis of their work A.I.E.E. Standards. Several such committees are in process of organization; each will cover a broad field. Among these are wires and cables, power switch gear, transformers, and measuring instruments. The sectional committee on rotating electrical machinery has been at work for a number of years. All of these group sectional committees are now under the sponsorship of the Electrical Standards Committee. The sectional committees on mercury arc rectifiers and on electric welding are about to complete their work, while the conflicts that have held up the final approval of the proposed American standard graphic symbols in the power, radio, and railway fields are apparently cleared up. The report of the same committee, but dealing with abbreviations for engineering and scientific terms has received approval as American Standard.

The work of the Sectional Committee on Electrical Definitions is proceeding in accordance with plans carefully outlined by its Executive Committee, taking into account the tremendous field to be covered and the numerous interests involved. From present indications, the committee will be able to offer its first report for the approval of the sponsor, the A.I.E.E., and the American Standards Association, some time next fall. Probably between 3,500 and 4,500 definitions will be included in the report, representing the work of eighteen subcommittees, with a personnel involving over 300. This committee has just accepted a new undertaking of considerable present interest, the standardization of the names and definitions of electron tubes used in radio and for general industrial purposes.

During the past year, the revised Code for Protection Against Lightning was approved. The A.I.E.E. and the Bureau of Standards are joint sponsors in this undertaking. The Code for School Lighting was also approved, and the Institute has appointed representatives to act on a committee charged with the development of a Ventilation Code.

In January of this year, the Institute gave official approval to the adoption of a new inch-millimeter conversion factor of 25.4, the result of a general industrial conference called in October, 1932, under the asupices of the American Standards Association.

Several new Standards publications were issued during the year as follows: Revisions of Standards Nos. 16 and 30, "Railway Control" and "Wires and Cables," respectively. The new Standards are Nos. 72 and 73 "Waterproof Wires and Cables" and "Heat Resisting Wires and Cables."

**U.S. National Committee of the I. E. C.**—The U.S. National Committee of the International Electrotechnical Commission has operated very satisfactorily during the past year in its reorganized form, two meetings of the committee having been held.

The committee suffered a severe loss in the death of its Honorary President, Dr. C. O. Mailloux, on October 14, 1932. Dr. Mailloux was recognized as one of the founders of the I.E.C. and the U.S.N.C. and was a moving spirit in both. He was an honorary president of the I.E.C. The other officers of the U.S.N.C. remain in office as reported last year.

In technical work progress has been made on specific projects during the past year as follows:

1. INTERNATIONAL ELECTROTECHNICAL VOCABULARY. A comprehensive vocabulary in French and English is under compilation. The work will be greatly facilitated by the draft report on electrical definitions issued during September, 1932, by the sectional committee on electrical definitions under the sponsorship of the American Institute of Electrical Engineers under the procedure of the A.S.A. A meeting of the advisory committee covering this subject was held in Paris in January, 1933, but the U.S.N.C. was unable to be represented at this meeting.

2. ELECTRICAL AND MAGNETIC MAGNITUDES AND UNITS. The names for the cgs units, magnetic flux, Maxwell; flux density, Gauss; magnetic field intensity, Oersted; magnetomotive force, Gilbert; adopted at the Oslo meeting in 1930, were agreed to at a meeting of the Symbols, Units, and Nomenclature Commission of the International Union of Pure and Applied Physics, held in Paris in July, 1932. This action brings these names for the units into a very strong position.

3. RATING OF ELECTRICAL MACHINERY. This advisory committee met in Paris in June, 1932. The U.S.N.C. was unable to have a representative present. The decisions reached at this meeting are at present being considered by the sectional committee on Rotating Electrical Machinery and will also be considered in the near future by the recently organized sectional committee on Transformers.

4. ELECTRIC TRACTION EQUIPMENT. A joint meeting of the advisory committee on Electric Traction Equipment—No. 9 and the Comite Mixte was held in Milan in April, 1933, the U.S.N.C. having two representatives present.

A meeting of the Committee of Action of the I.E.C. which corresponds to an executive committee, was held in Paris in January, 1933. The work of the Commission in general was reviewed and two new advisory committees, one covering wires and cables and another storage batteries, were authorized. The U.S.N.C. has not yet decided whether it will participate in these new projects. Plans were made for the next plenary meeting of the I.E.C. which is to be held in Prague, Czechoslovakia, in 1934. The Committee of Action also accepted rules of procedure for the advisory committees, subject to the ratification of the plenary meeting in 1934, as well as a modification of the constitution and functions of the Committee of Action, also subject to ratification by the plenary meeting at Prague in 1934.

A meeting of the advisory committee on Internal Combustion Engines—No. 19, for which the U.S.N.C. holds the secretariat, is to be held in this country, probably in September of this year, at which a substantial foreign delegation will be present. A meeting of the advisory committee on Electrical Measuring Instruments—No. 13 is at present scheduled to be held in Paris in June.

The following standards of the I.E.C. are available in printed form and may be obtained from the offices of the U.S.N.C. at 29 West 39th Street, New York City:

International symbols: Part 1, letter symbols, publication 27, December, 1920. Part 2, graphical symbols for heavy-current systems, publication 35, 1930. Part 3, graphical symbols for weak-current systems, publication 42, 1931.

International standard of resistance for copper, publication 28, March, 1925.

Rules for electrical machinery, publication 34, 1930.

Standard dimensions of bayonet lamp sockets and caps, publication 37, 1927.

Standard voltages, publication 38, 1927.

International rules for traction motors, publication 39, 1927.

Publication on the testing of hydraulic turbines, publication 41, 1928.

Recommendations for alternating-current watt-hour meters, publication 43, 1931.

Recommendations for instrument transformers, publication 44, 1931.

Publication on steam turbines: Part 1, specifications, publication 45, 1931. Part 2, rules for acceptance tests, publication 46, 1931.

Definitions and rules for switchgear, publication 47, 1932.

**Coördination Committee.**—In accordance with past practice, the committee corresponded with District and Section officers to obtain their views regarding any national conventions and District meetings desired in their respective Districts during the calendar year 1934. On account of economic conditions, the committee recommended to the Board of Directors, at its meeting held on January 25, 1933, that the adoption of a schedule of 1934 meetings be postponed to the May meeting of the Board, and this recommendation was approved.

**Committee on Transfers.**—Numerous discussions, in recent years, of methods of encouraging Institute members who are qualified for the higher grades to submit their applications for transfer resulted in recommendations by the Conference of Officers, Delegates, and Members, in 1931, and later by the Committee on Coördination of Institute Activities which caused the Board of Directors to approve, in January, 1932, the appointment of a national standing committee on transfers and the encouragement of the appointment of a suitable committee by each Section.

The functions of the national committee are to prepare literature which will encourage qualified members to apply for transfer and to coördinate the activities of the Sections in connection with transfers. Each local committee is expected to study the qualifications of members of its Section and to urge those who are fully qualified for higher grades to apply for transfer.

In October, 1932, the national Committee on Transfers distributed to all Sections a statement regarding the functions of the committees, reasons for transferring to the grades of Fellow and Member, and suggestions with regard to desirable types of procedure. Many of the Sections appointed committees which were active in stimulating the submission of applications.

**Committee on Legislation Affecting the Engineering Profession.**—The committee considered the April 15, 1932, edition of "A Model Law for the Registration of Professional Engineers and Land Surveyors," which had been prepared by a group of representatives of various engineering societies. Its report was presented at the meeting of the Board of Directors held on January 25, 1933, and was referred to the Public Policy Committee for recommendation.

**Committee on the Economic Status of the Engineer.**—The activities of this committee were largely concerned with conferences which led to the organization on October 3, 1932, of Engineers' Council for Professional Development. The committee considered various other matters which had been referred to it.

**Committee on Safety Codes.**—No specific matters were presented to this committee as a committee for review or action during this year.

The chairman of the committee, however, can report on certain items of individual activity as representative of the Institute or of the committee.

Chairman A. R. Small, of the Electrical Committee of the National Fire Protection Association, appointed in August, 1932, a special committee to handle a somewhat controversial subject for report to the Electrical Committee at its annual meeting in March, 1933. Mr. Small appointed as chairman of this special committee, the representative of the American Institute of Electrical Engineers, serving on the Electrical Committee, who was also chairman of the A.I.E.E. Committee on Safety Codes.

The subject in question which was handled by this special committee was the Use of Bare Neutral Wiring in Interior Wiring Systems.

This special committee has functioned satisfactorily. Its report was submitted to, and accepted by, the annual meeting of the Electrical Committee of the N.F.P.A. at its meeting in March, 1933.

As indicated, the foregoing was not activity of the Committee on Safety Codes as a committee, but rather activity of the chairman, and as representative of the A.I.E.E. on the Electrical Committee of the National Fire Protection Association.

In addition to the foregoing, a member of the Committee on Safety Codes (Dr. M. G. Lloyd) acted as representative of the American Institute of Electrical Engineers at the meeting of the National Fire Waste Council, held on April 7, 1933, in Washington.

**Technical Committees.**—The technical committees continued their activities in the stimulation of the preparation of desirable papers in their respective fields and in the review of papers submitted to the Institute for presentation and publication. Information on meetings, papers, and publications is given on other pages of this report.

**Membership Committee.**—Because of general business conditions adversely affecting Institute membership, the Membership Committee was unusually active during the current year. The results of these activities are summarized briefly as follows:

1. The usual letter was sent to the entire membership requesting that they retain their membership in good standing, stimulate similar action on the part of fellow members, personally solicit prospects who are technically and financially able to join the Institute, and finally to boost the Institute continually. A form was attached to this letter giving the names and addresses of the chairmen of all Section membership committees, with a tear-off section provided to fill in the names and addresses of prospective members. This assisted the local committees in soliciting new members during the year.

2. A questionnaire was submitted to the Membership Committee of each section asking for various kinds of information as to the exact routine of handling membership activities. The results were carefully studied, and indicated a lack of general uniformity in handling this important local work.

3. A letter was then addressed to each section executive committee and membership committee requesting, after joint due deliberation, the answer to two simple non-leading questions:

A—How can the activities of the Institute be so improved as to attract to its membership those who are eligible to join?
B—How can the activities of the membership committees, both local and national, be improved to best present advantages of membership to prospects?

Thirty-eight sections submitted detailed reports on these all-important questions.

4. The Membership Committee then held a meeting in Pittsburgh on November 18, 1932, at which time it carefully discussed all phases of membership activities and particularly the suggestions of the various sections of ways and means of improving the attractiveness of Institute membership. This meeting resulted in the Chairman being instructed to prepare a detailed report summarizing the results of the various data collected throughout the year.

5. On March 8, 1933, a sixty-eight page report analyzing the various data assembled was issued in its tentative form, this report being divided into three parts as follows:

Part I—Comments on Institute activities.
Part II—Proposed membership information pamphlet.
Part III—Simplified membership policy.

Part I of this report is unusually interesting, giving as it does the opinions of a large percentage of the membership as reflected through the local organization of 38 sections. It frankly and fully discusses some very pertinent points regarding Institute activities and suggested changes thereto. Part II develops a proposed membership information pamphlet somewhat along the lines of a sales prospectus, as the Membership Committee considers the securing of new members under present conditions primarily a sales proposition. Part III closes with suggested methods for standardizing and simplifying the membership routine in all of the sections.

Upon instruction of the President, this report is now being carefully studied by the administration and various interested committees.

6. In spite of the adverse business conditions and the amount of work involved in the collection of the above-mentioned material, 979 applications were received during the year. The additions to and deductions from the membership during the year are given in the following table:

| | Honorary | Fellow | Member | Six-year Associate | Associate | Total |
|---|---|---|---|---|---|---|
| Membership on April 30, 1932 | 9 | 738 | 3,871 | 6,753 | 6,178 | 17,549 |
| Additions: | | | | | | |
| Transferred | 1 | 23 | 135 | | | |
| New members qualified | | 2 | 45 | 4 | 765 | |
| Reinstated | | 3 | 8 | 15 | 17 | |
| Total | 10 | 766 | 4,059 | 6,772 | 6,960 | 18,567 |
| Deductions: | | | | | | |
| Died | 1 | 19 | 25 | 37 | 12 | |
| Resigned | | 14 | 118 | 490 | 300 | |
| Transferred | | 1 | 18 | 125 | 15 | |
| Dropped | | 3 | 35 | 177 | 158 | |
| Membership on April 30, 1933 | 9 | 729 | 3,863 | 5,943 | 6,475 | 17,019 |

7. The Membership Committee takes this opportunity to express sincere appreciation to the local administrations and membership committees for their wholehearted coöperation in assembling the important information included in the Membership Committee's special report.

**Deaths.**—The following deaths have occurred during the year.

*Honorary Member:* John J. Carty.

*Fellows:* Harry Alexander, William H. Blood, Jr., Alphonse L. Drum, Charles W. Hutton, Warren B. Lewis, C. O. Mailloux, Robert Orstettich, Horace F. Parshall, William H. Patchell, Nelson L. Pollard, Samuel Reber, Frederick L. Rhodes, William Lispenard Robb, R. F. Schuchardt, Franklin W. Springer, Roy M. Stanley, Lewis L. Tatum, Robert B. Williamson, Robert M. Wilson.

*Members:* Mangus W. Alexander, Basil C. Battye, Daniel H. Braymer, Frederick B. Brown, W. T. Kendall Brown, George Crisson, William L. Dodge, Park Elliott, George Ferguson, Clarence S. Hammatt, William W. Handy, Edwin M. Herr, Frank B. Lamb, Fred M. Laxton, Arthur W. Little, Alfred F. Masury, Henry E. McGowan, John O. Montignani, M. P. Ryder, Edwin N. Sanderson, Harold Seaburg, F. D. Smith, H. O. Swoboda, William W. Tefft, Harry N. Van Deusen.

*Associates:* Walter Arnstein, Alfred B. Atkinson, George P. Baldwin, William A. Barrett, Thaddeus R. Beal, Henry W. Beers, Sol D. Benoliel, H. B. Brigham, Thomas F. Corcoran, Herbert Edwards, Charles E. Eveleth, Louis G. Freeman, John R. Gilroy, Charles F. Goob, Harry W. Hadlock, William J. Harvie, Frank Haye, W. R. Hendrey, William H. Hill, John S. Jenks, Frederick W. Kelley, Harold C. Klingenschmitt, John E. Konze, Max Kushlan, John J. L. Manning, Ira B. Matthews, Yosinobu Matunga, Charles S. McGill, Thomas McLean, Alfred Menefoglio, Frank T. Morrissey, Delos E. Parsons, Robert O. Pennell, Archibald J. Robertson, Rudolph Rosenstengel, Arthur H. Savage, Frank R. Schmid, H. F. L. J. Seyler, James A. Shepard, Louis N. Stoskopf, George C. Sutton, Jin Tachihara, Richmond Talbot, Leonard G. Van Ness, Reginald H. Wilmot, Walter L. Woodmansee, William F. Yeager, Henry L. Zabriskie, Bauke Zondervan.

**Board of Examiners.**—The Board of Examiners held eight meetings during the past year, averaging about three hours, and considered 2,242 cases, divided as shown in the following table:

| | | |
|---|---|---|
| **Applications for Admission** | | |
| Recommended for grade of Associate | 690 | |
| Not recommended | 11 | 701 |
| Recommended for grade of Member | 40 | |
| Not recommended | 6 | 46 |
| Recommended for grade of Fellow | 1 | |
| Not recommended | 1 | 2 |
| Recommended for enrollment as Students | | 1,342 |
| **Applications for Transfer** | | |
| Recommended for grade of Member | 109 | |
| Not recommended | 11 | 120 |
| Recommended for grade of Fellow | 29 | |
| Not recommended | 2 | 31 |
| | | 2,242 |

**Institute Prizes.**—Four national prizes ($100 each) and fifteen District prizes ($25 each), for papers presented in 1931, were announced on page 418 of the June, 1932, issue of ELECTRICAL ENGINEERING. The national prizes were presented at the Summer Convention in Cleveland, and the District prizes were presented at various meetings in the respective Districts.

**Scholarships.**—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute Committee. Each scholarship pays $350 toward annual tuition, with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

**Edison Medal.**—The Edison Medal, founded by associates and friends of the late Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1932 was awarded to Bancroft Gherardi, "for his contributions to the art of telephone engineering and the development of electrical communication." The medal was presented at the Winter Convention of the Institute, January 25, 1933.

**John Fritz Medal.**—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the twenty-ninth medal to Daniel Cowan Jackling.

**Lamme Medal.**—The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, Chief Engineer of the Westinghouse Electric & Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of two such medals in some years if the accumulation from the funds warrants.

The Lamme Medal Committee of the Institute awarded the fifth (1932) Lamme Medal to Dr. Edward Weston, "for his achievements in the development of electrical apparatus, especially in connection with precision measuring instruments." Arrangements are being made for the presentation of the medal at the annual Summer Convention at Chicago, Ill., June 26–30, 1933.

**Alfred Noble Prize.**—This prize, established in 1929, consists of a certificate and a cash award of $500 from the income from a fund contributed by engineers and others to perpetuate the name and achievements of Alfred Noble, past-president of the A.S.C.E. and of the Western Society of Engineers. It is made to a member of any of the coöperating societies, A.S.C.E., A.I.M.E., A.S.M.E., A.I.E.E., or W.S.E., for a technical paper of particular merit accepted by the publication committee of any of these societies, provided the author, at the time of such acceptance, is not over 30 years of age.

The second award (1932) was made to Frank M. Starr, of the General Electric Company, Schenectady, N. Y., an Associate in the A.I E.E., for his paper *Equivalent Circuits—I*, which was presented at the 1932 Winter Convention.

**Commission of Washington Award.**—This award may be made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A.S.C.E., the A.I.M.E., the A.S.M.E., and the A.I.E.E. No award was made for the year 1933.

**Employment Service.**—The Institute coöperates with the national societies of civil, mining, and mechanical engineers in the operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others coöperate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society, and the Engineers' Club of San Francisco.

The New York office has been coöperating closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the Employment Service announcements monthly in ELECTRICAL ENGINEERING, weekly subscription bulletins are issued for those seeking positions.

**American Engineering Council.**—This organization, including in its membership more than twenty national, state, and local engineering societies has continued to represent its constituents in matters affecting the public welfare and involving the engineering and allied technical professions.

During the past year, recommendations were made concerning many bills presented in the Congress of the United States, and much attention was given to methods of reducing unemployment among engineers as well as to studies of the causes which produced the depression, and methods of reducing business instability. The Committee on Relation of Consumption, Production, and Distribution presented its second progress report. The Council sponsored the formation of and coöperated in the activities of Committees on Engineers and Employment which were organized in nearly all of the states.

The wide range of types of work carried on by the Council is indicated by the names of its special committees for 1933, including the following: Administration of Public Works; Airports; Air Transport Service in Foreign Countries; Bridges; Communications; Competition of Governmental Agencies with Engineers in Private Practice; Corps of Engineers; Engineering Features of Public Domain Report; Engineers and Employment; Engineers Water Power Policy; Flood Control; Government Expenditures; Naval Towing Tank; Oil Pollution of Streams; Patents; Public Works Program of A.S.C.E.; Reforestation; Relation of Consumption, Production, and Distribution; State Engineering Councils; Street Traffic Signs, Signals, and Markings; Telephone Directory Classification of Engineers; and Water Resources.

On account of economic conditions, the publication of the A.E.C. Bulletin was suspended in December, 1931, and it was replaced in part by a monthly news release entitled "Engineering News from Washington, D. C."

**United Engineering Trustees, Inc.**—This organization, formerly United Engineering Society, was set up by the four national societies of civil, mining, mechanical, and electrical engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the Library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual report of the United Engineering Trustees, Inc., were published on page 209 of the March 1933,, issue of ELECTRICAL ENGINEERING.

**Engineering Foundation.**—This department of United Engineering Trustees, Inc., was established in 1914 by the national societies of civil, mining, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made four gifts toward its endowment. The fund has been generously increased through the gifts of the late Edward D. Adams and Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects, and coöperation has been extended in others.

**Engineering Societies Library.**—The Library is administered as a free public library under the direction of the Library Board of United Engineering Trustees, Inc., this Board being composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers.

The Library contains about 133,273 books and pamphlets. It receives regularly about 1,200 technical periodicals in many languages, and many additional publications issued irregularly.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searches, etc. Special arrangements have been made for lending books.

**Representatives.**—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years. A complete list of representatives was published in the September issue of ELECTRICAL ENGINEERING.

**Finance Committee.**—During the year the committee has held meetings frequently, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins & Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the Board of Directors,

H. H. HENLINE,

*National Secretary.*

May 22, 1933.

**HASKINS & SELLS**
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 17, 1933.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have examined your accounts for the purpose of verifying the stated financial condition at April 30, 1933, and have audited your records of cash receipts and disbursements for the year ended that date. We submit the following exhibits and schedule:

Exhibit
- A—Balance Sheet, April 30, 1933.
    - Schedule 1—Property and Restricted Funds—Securities, Cash and Accrued Interest Receivable.
- B—Statement of Cash Receipts and Disbursements of General Funds for the Year Ended April 30, 1933.
- C—Statement of Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1933.

In our opinion Exhibit A sets forth your financial condition at April 30, 1933, and Exhibits B and C set forth your receipts as recorded and your disbursements during the year ended that date.

Yours truly,
Haskins & Sells

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
### BALANCE SHEET, APRIL 30, 1933

EXHIBIT A.

### ASSETS

| | | |
|---|---|---|
| **PROPERTY FUND INVESTMENTS:** | | |
| One-fourth interest in real estate and other assets of United Engineering Trustees, Inc., exclusive of Trust Funds | $496,948.48 | |
| Equipment: | | |
| Library—Volumes and fixtures | 37,296.37 | |
| Works of art etc. | 3,001.35 | |
| Office furniture and fixtures (less reserve for depreciation, $19,160.45) | 13,312.45 | |
| Securities—Schedule 1 | 10,065.00 | |
| Total property fund investments | | $560,623.65 |
| **RESTRICTED FUND INVESTMENTS**—Schedule 1: | | |
| Securities—At cost (less reserve for bonds of doubtful value) | $167,493.55 | |
| Cash | 8,036.80 | |
| Accrued interest receivable | 223.33 | |
| Total restricted fund investments | | 175,753.68 |
| **CURRENT AND WORKING ASSETS:** | | |
| Cash | $ 15,648.46 | |
| Accounts receivable: | | |
| Members—For dues | 44,792.40 | |
| Advertisers | 282.00 | |
| Miscellaneous | 3,524.19 | |
| Accrued interest on investments | 2,374.94 | |
| Inventories: | | |
| "Quarterly Transactions," etc. | 5,164.64 | |
| Text and cover paper | 1,550.56 | |
| Badges | 806.03 | |
| Total current and working assets | | 74,143.22 |
| Total | | $810,520.55 |

### LIABILITIES

| | | |
|---|---|---|
| ***PROPERTY FUND RESERVE** | | $560,623.65 |
| **RESTRICTED FUND RESERVES:** | | |
| Reserve Capital Fund | $154,528.25 | |
| Life Membership Fund | 10,921.58 | |
| International Electrical Congress of St. Louis Library Fund | 4,609.89 | |
| Lamme Medal Fund | 4,665.78 | |
| Mailloux Fund | 1,028.18 | |
| Total restricted fund reserves | | 175,753.68 |
| **CURRENT LIABILITIES:** | | |
| Accounts payable | $ 5,809.38 | |
| Dues received in advance | 2,029.79 | |
| Entrance fees and dues advanced by applicants for membership | 253.50 | |
| Subscriptions for "Quarterly Transactions" received in advance | 114.50 | |
| Total current liabilities | | 8,207.17 |
| **SURPLUS** | | 65,936.05 |
| Total | | $810,520.55 |

* At April 30, 1932, Property Fund Reserve was included in surplus.

NOTE: In accordance with the usual practice of the Society, no provision has been made for dues which may prove to be uncollectable.

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## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### PROPERTY AND RESTRICTED FUNDS SECURITIES, CASH, AND ACCRUED INTEREST RECEIVABLE, APRIL 30, 1933

EXHIBIT A
SCHEDULE 1

| SECURITIES | Number of Shares of Stock or Face Value of Bonds | Property Fund (Equipment Replacements) | Restricted Funds: Reserve Capital Fund | Restricted Funds: Life Membership Fund | Restricted Funds: International Electrical Congress of St. Louis Library Fund | Restricted Funds: Lamme Medal Fund | Restricted Funds: Mailloux Fund | Total |
|---|---|---|---|---|---|---|---|---|
| **RAILROAD BONDS:** | | | | | | | | |
| Baltimore & Ohio Railroad Company 6% Refunding and general mortgage series C, due 1995 | $12,000.00 | | $8,940.00 | | | $4,330 00 | | $13,270.00 |
| Central of Georgia Railway Company 5% consolidated mortgage, due 1945 | 3,000.00 | | 1,477.50 | | | | | 1,477.50 |
| Chicago & Erie Railroad Company 5% first mortgage, due 1982 | 1,000.00 | | 1,105.00 | | | | | 1,105.00 |
| Chicago, Burlington & Quincy Railroad Company 4%, due 1958 | 5,000.00 | | | $4,868.75 | | | | 4,868.75 |
| Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series A, due 1971 | 1,000.00 | | 1,010.00 | | | | | 1,010.00 |
| Chicago & Northwestern Railway Company 6½%, due 1936 | 9,000.00 | | 7,202.50 | | | | | 7,202.50 |
| Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage, due 1960 | 8,000.00 | | 7,940.00 | | | | | 7,940.00 |
| Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 (certificates of deposit) | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| New York Central Railroad Company 5% refunding and improvement mortgage series C, due 2013 | 6,000.00 | | 5,742.50 | | | | | 5,742.50 |
| Pennsylvania Railroad Company 4½% general mortgage series A, due 1965 | 5,000.00 | | 5,130.00 | | | | | 5,130.00 |
| St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 (certificate of deposit) | 6,000.00 | | 5,497.50 | | | | | 5,497.50 |
| Southern Railway Company 5% first consolidated mortgage, due 1994 | 1,000.00 | | 980.00 | | | | | 980.00 |
| Western Pacific Railroad Company 5% series A, due 1946 | 15,000.00 | | 7,225.00 | | | | | 7,225.00 |
| Total railroad bonds | | | $62,068.75 | $4,868.75 | | $4,330.00 | | $71,267.50 |
| **PUBLIC UTILITY BONDS.** | | | | | | | | |
| Consolidated Gas Company of New York 5½% debentures, due 1945 | $5,000.00 | | $5,187.50 | | | | | $5,187.50 |
| Duquesne Light Company 4½% first mortgage series A, due 1967 | 3,000.00 | | 2,970.00 | | | | | 2,970.00 |
| Hydro-Electric Power Commission of Ontario 3½%, due 1952 | 4,500.00 | | 4,500.00 | | | | | 4,500.00 |
| New York Telephone Company 4½%, due 1939 | 2,000.00 | | | | $ 878.75 | | $1,000.00 | 1.878.75 |
| Pacific Gas & Electric Company 5½%, first and refunding mortgage series C, due 1952 | 5,000.00 | | 5,137.50 | | | | | 5,137.50 |
| Philadelphia Company secured 5% series A, due 1967 | 10,000.00 | | 10,000.00 | | | | | 10,000.00 |
| Shawinigan Water & Power Company 4½% first mortgage and collateral trust sinking fund series A, due 1967 | 5,000.00 | | 4,581.25 | | | | | 4.581.25 |
| Texas Electric Service Company 5% first mortgage, due 1960 | 4,000.00 | | 3,910.00 | | | | | 3.910.00 |
| United Light & Power Company 5½% first lien and consolidated mortgage, due 1959 | 5,000.00 | | 4,975.00 | | | | | 4,975.00 |
| Total public utility bonds | | | $41,261.25 | | $ 878 75 | | $1,000.00 | $43.140.00 |
| **INDUSTRIAL BONDS** | | | | | | | | |
| American Smelting & Refining Company 5% first mortgage series A, due 1947 | $9,000.00 | | $9,085.00 | | | | | $9.085.00 |
| Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund, due 1936 | 5,000.00 | | 5,033.75 | | | | | 5,033.75 |
| Cleveland Union Terminals Company 5% sinking fund series B. due 1973 | 4,000.00 | $4,010.00 | | | | | | 4.010.00 |
| Industrial bonds—(Forward) | | $4.010.00 | $14.118.75 | | | | | $18.128.75 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### PROPERTY AND RESTRICTED FUNDS SECURITIES, CASH, AND ACCRUED INTEREST RECEIVABLE, APRIL 30, 1933

EXHIBIT A.

SCHEDULE 1

| | | | Restricted Funds | | | | | |
|---|---|---|---|---|---|---|---|---|
| SECURITIES—*Continued* | Number of Shares of Stock or Face Value of Bonds | Property Fund (Equipment Replacements) | Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund | Total |
| Total railroad bonds—(Forward) | | | $62,068.75 | $4,868.75 | | $4,330.00 | | $71,267.50 |
| Total public utility bonds—(Forward) | | | $41,261.25 | | $ 878.75 | | $1,000.00 | $43,140.00 |
| Industrial bonds—(Forward) | | $4,010.00 | $14,118.75 | | | | | $18,128.75 |
| Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.) 5½%, due 1933 | $15,000.00 | 1,000.00 | 14,000.00 | | | | | 15,000.00 |
| International Match Corporation 5% convertible debentures, due 1941 (certificate of deposit) | 3,000.00 | | 2,880.00 | | | | | 2,880.00 |
| New York Steam Corporation 6% first mortgage, due 1947 | 10,000.00 | | 10,837.50 | | | | | 10,837.50 |
| United States Rubber Company 5% first and refunding mortgage series A, due 1947 | 2,000.00 | | 1,915.00 | | | | | 1,915.00 |
| Western Electric Company 5% debentures, due 1944 | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| Youngstown Sheet and Tube Company 5% first mortgage sinking fund series A, due 1978 | 10,000.00 | | 10,137.50 | | | | | 10,137.50 |
| Total industrial bonds | | $5,010.00 | $63,707.50 | | | | | $68,717.50 |
| MUNICIPAL BONDS: | | | | | | | | |
| New York City 4½% corporate stock, due 1957 | 2,000.00 | | | | $2,204.05 | | | $ 2,204.05 |
| CAPITAL STOCKS: | | | | | | | | |
| Commonwealth Edison Company | 12 shares | | $2.892.00 | | | | | $ 2,892.00 |
| Consolidated Gas Company of New York, $5.00 cumulative preferred | 30 " | $3,060.00 | | | | | | 3,060.00 |
| Public Service Corporation of New Jersey, $5.00 preferred | 30 " | | 2,958.75 | | | | | 2,958.75 |
| United Gas Improvement Company, $5.00 preferred | 30 " | 1,995.00 | 997.50 | | | | | 2,992.50 |
| Total capital stocks | | $5,055.00 | $6,848.25 | | | | | $11,903.25 |
| Total securities | | $10,065.00 | $173,885.75 | $4,868.75 | $3,082.80 | $4,330.00 | $1,000.00 | $197,232.30 |
| LESS RESERVE FOR BONDS OF DOUBTFUL VALUE: | | | | | | | | |
| Central of Georgia Railway Company 5% consolidated mortgage, due 1945 | $3,000.00 | | $1,477.50 | | | | | $1,477.50 |
| Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 | 10,000.00 | | 9,818.75 | | | | | 9,818.75 |
| International Match Corporation 5% convertible debentures, due 1941 | 3,000.00 | | 2,880.00 | | | | | 2,880.00 |
| St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 | 6,000.00 | | 5,497.50 | | | | | 5,497.50 |
| Total reserve for bonds of doubtful value | | | $19,673.75 | | | | | $19,673.75 |
| TOTAL SECURITIES, LESS RESERVE | | $10,065.00 | $154,212.00 | $4,868.75 | $3,082.80 | $4,330.00 | $1,000.00 | $177,558.55 |
| CASH | | | 316.25 | 6,019.50 | 1,459.59 | 235.78 | 5.68 | $ 8,036.80 |
| ACCRUED INTEREST RECEIVABLE | | | | 33.33 | 67.50 | 100.00 | 22.50 | 223.33 |
| Total property fund securities | | $10,065.00 | | | | | | $10,065.00 |
| Total restricted fund investments | | | $154,528.25 | $10,921.58 | $4,609.89 | $4,665.78 | $1,028.18 | $175,753.68 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Statement of Cash Receipts and Disbursements of General Funds for the Year Ended April 30, 1933

Exhibit B.

| | | |
|---|---|---|
| Cash on Deposit May 1, 1932, with the National City Bank of New York | | $ 14,505.84 |
| **Receipts:** | | |
| Dues (including $60,391.25 allocated to "Electrical Engineering" subscriptions) | $165,182.85 | |
| Advertising | 21,678.62 | |
| "Quarterly Transactions" subscriptions | 11,033.83 | |
| "Electrical Engineering" subscriptions | 6,744.00 | |
| Miscellaneous publications, etc. | 4,586.59 | |
| Students' fees | 6,116.55 | |
| Entrance fees | 3,109.16 | |
| Badges | 1,078.71 | |
| Transfer fees | 783.14 | |
| Miscellaneous | 47.23 | |
| Interest on investments and bank balances | 10,257.51 | |
| Transfer from Reserve Capital Fund, per resolution of Board of Directors on October 12, 1932 | 15,519.00 | |
| Total receipts | | 246,137.19 |
| Total | | $260,643.03 |
| **Disbursements:** | | |
| Publication expenses: | | |
| "Electrical Engineering" | $ 58,918.85 | |
| "Quarterly Transactions" | 17,922.89 | |
| Technical papers | 13,904.29 | |
| Year book | 2,575.97 | |
| Miscellaneous | 2,731.10 | |
| Administrative expenses | 42,605.88 | |
| Institute Sections | 28,997.34 | |
| Institute meetings | 11,530.34 | |
| Institute Branches | 2,832.10 | |
| American Engineering Council | 13,504.32 | |
| Forward | $195,523.08 | $260,643.03 |
| Total—(Forward) | | $260,643.03 |
| Disbursements—(Forward) | $195,523.08 | |
| Traveling expenses: | | |
| Board of Directors | 3,706.00 | |
| Branch Counselors | 5,193.54 | |
| Geographical districts: | | |
| Executive Committees | 1,343.85 | |
| Vice-Presidents | 1,048.34 | |
| National Nominating Committee | 994.90 | |
| United Engineering Trustees, Inc.: | | |
| Library assessment | 8,936.00 | |
| Building assessment | 4,111.05 | |
| Standards Committee | 8,434.36 | |
| Membership Committee | 5,534.72 | |
| Employment service | 3,466.60 | |
| American Standards Association | 1,500.00 | |
| Badges | 1,009.21 | |
| Exchange | 941.75 | |
| Retirement salary | 900.00 | |
| Institute prizes | 428.59 | |
| Finance Committee | 380.64 | |
| United States National Committee of International Commission on Illumination | 300.00 | |
| Geographical district prizes: | | |
| Best branch paper | 162.00 | |
| Best paper | 76.50 | |
| Initial paper | 76.50 | |
| John Fritz medal | 140.00 | |
| Technical Committee | 138.74 | |
| Headquarters Committee | 80.71 | |
| Code Committee | 60.00 | |
| Edison Medal Committee | 54.65 | |
| Repayment of funds to the Professional Engineers Committee on Unemployment | 251.95 | |
| Transfer to Reserve Capital Fund | 200.89 | |
| Total disbursements | | $244,994.57 |
| Cash on Deposit April 30, 1933, with The National City Bank of New York | | $ 15,648.46 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### Statement of Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1933

Exhibit C.

| | | | Restricted Funds | | | | |
|---|---|---|---|---|---|---|---|
| | Total | Property Fund (Equipment) Replacements) | Reserve Capital Fund | Life Membership Fund | International Electrical Congress of St. Louis Library Fund | Lamme Medal Fund | Mailloux Fund |
| Cash on Deposit May 1, 1932, with East River Savings Bank and National City Bank of New York | $15,043.33 | $296.81 | $6,799.11 | $6,359.09 | $1,371.60 | $215.78 | $ 0.94 |
| **Receipts:** | | | | | | | |
| Proceeds from sale of securities | $31,740.25 | | $31,740.25 | | | | |
| Interest on bonds | 620.00 | | | $ 200.00 | $ 135 00 | $ 240.00 | $45.00 |
| Life membership fees | 250.12 | | | 250.12 | | | |
| Transfer from General Fund | 200.89 | | 200.89 | | | | |
| Interest on bank balances | 152.98 | | | 152.98 | | | |
| Total receipts | $32,964.24 | | $31,941.14 | $ 603.10 | $ 135.00 | $ 240.00 | $45.00 |
| Total | $48,007.57 | $ 296.81 | $38,740.25 | $6,962.19 | $1,506.60 | $ 455.78 | $45.94 |
| **Disbursements:** | | | | | | | |
| Purchase of securities | $15,905.00 | | $15,905.00 | | | | |
| Transfer to General Fund, per resolution of Board of Directors on October 12, 1932 | 15,519.00 | | 15,519.00 | | | | |
| Annual withdrawal authorized in by-laws | 942.69 | | | $ 942.69 | | | |
| Bronze and gold replicas of Lamme Medal | 220.00 | | | | | $ 220.00 | |
| All other disbursements | 7,384.08 | $ 296.81 | 7,000.00 | | $ 47.01 | | $40.26 |
| Total disbursements | $39,970.77 | $ 296.81 | $38,424.00 | $ 942.69 | $ 47.01 | $ 220.00 | $40.26 |
| Cash on Deposit April 30, 1933, with East River Savings Bank and National City Bank of New York | $8,036.80 | | $ 316.25 | $6,019.50 | $1,459.59 | $ 235.78 | $ 5.68 |